

dti

**ENVIRONMENTAL IMPACTS OF
THE EXTRACTION OF FORESTRY
RESIDUES**

Project Report

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EXECUTIVE SUMMARY

Introduction

In the United Kingdom (UK), interest in the removal of forest residues has been renewed by the possibility of using the biomass for energy generation. The use of residues may aid the UK government's New & Renewable Energy policy. Biomass will play an important role in meeting the target of generating 10% of electricity from renewable energy by 2010. The implementation of this policy could lead to the establishment of between 100,000 and 150,000 ha of energy crops in England and Wales but the target may be reduced by the use of forestry residues. However, there are potential environmental impacts associated with the removal of forest residues. In the UK, these are:

- preservation of sustainable forest productivity;
- protection of soil structure and the soil resource;
- maintenance of water quality, through the control of sediment transport;
- maintenance of bio-diversity;
- carbon sequestration; and
- woodland amenity, access.

Project Aims and Objectives

The project aimed to assess the environmental implications of the shift in forestry operation and management practice necessary to supply significant quantities of fuel wood in the timeframe to 2020. The project achieved this by two principal mechanisms:

- a review of current forestry practices for the treatment of residues and the production of wood fuels and their impacts on air, land, water, flora and fauna, including soil and landscape: and
- modelling of scenarios to identify the quantity of forestry land from which residues may be available.

The output of the review and models was used to conclude how practices may develop and how current environmental impacts may change as a result of the removal of forestry residues. The exercise exposed gaps in knowledge for

scenario setting into the future. This was supported by detailed discussions with stakeholders of the UK forestry industry.

The report was to be forward looking: guidelines for the monitoring of a scheme that will test the conclusions of the report have been presented. We have endeavoured to report in a way accessible to forestry professionals, environmental professionals, and the concerned layperson, for this was a specific objective of the project.

Background

The environmental impacts of residue removal may be considered from published sources but the limitations to a change of practice are not well documented for UK conditions. Information may be supplemented from two sources. The first is the understanding of the issues and constraints within the UK forestry profession and timber harvesting skill base. The second is the creation of geographic information system (GIS) models employing soil, topography, forest area, and climate data. These models can be used to consider scenarios, based on impact thresholds, to produce assessments on the proportion of forest areas from which residues may become available.

This project sits alongside another DTI sponsored project which quantified the woodfuel resource. We believe that yield data could be incorporated into our models of environmental impact and developed nationally to inform policymakers and investors in biomass energy. The model was not intended as, and will never be suitable for, a site management tool. Nonetheless, the soil parameters on which the models have been based provide a checklist of environmental considerations, for managers, providing a decision support mechanism.

Summary of Methodology Adopted

A review of the knowledge base on whole tree harvesting and its environmental impacts was conducted using published sources and discussions with the forestry and biomass energy industries. Whilst we

considered our results to be relevant also to Northern Ireland, our discussions embraced a wide geographic spread only within Great Britain.

The selection of case study areas, on which GIS models were tested, was similarly broad, but not random. It was important to embrace a range of soil types and to seek areas where forestry was a major land use. A number of datasets, based on 1:250 000 soil maps, and common to both Scotland and England and Wales have been adopted. These were:

- critical loads of acid deposition;
- erosion risk, based on topography;
- groundwater vulnerability, based on geology and soils;
- soil compaction risk based on soil moisture retention characteristics, integrated with climatic parameters; and
- soil fertility for tree growth, which employs soil pH.

Only the physical/chemical impacts associated with whole tree harvesting, listed above, can be modelled. Carbon sequestration and biodiversity impacts were excluded, along with any other issues that may create the policy/management drivers behind decisions to harvest forest residues.

Thresholds for each data layer have been selected, representing an assessment of each individual impact on the suitability of a site for residue extraction. In practice the terms highly, moderately and marginally suitable may refer to the likely degree of impact (for example, acidity load) or to differing periods of time in which site conditions permit residue extraction (such as soil wetness). The term unsuitable is applied to those areas when typically there is no opportunity during the year to traffic the soils without environmental damage or at a very limited number of sites which have an exceptionally high acidification risk.

Harvesting of residues which have been used as brashmats and trafficked is not a realistic prospect because of soil contamination. Currently, the model is insufficiently sophisticated to enable division between non-harvested brashmat material and surplus harvestable residues.

Conclusions and Recommendations

The model outputs differentiate clearly between opportunities for residue harvesting between upland forestry in the north and west of the UK and lowland forestry in the south. This reflects the different biophysical conditions but, whilst cumulatively the distinction between upland and lowland forestry is reasonably clear, in fact there was considerable variation in the way these cumulative scores were derived.

For example, the acidification risk at Morven and Aros, on the west coast of Scotland matches more closely those of southern England than with the other upland sites. A large part of the case study area comprises tertiary basalts, which are relatively base-rich, in comparison to the predominantly acid metamorphic and sedimentary rocks of the other case sites in Scotland and in Wales.

The contrast in the soil compaction assessment between case sites in the west and those in the east was very marked. Parts of the Morven and Aros area in particular comprise poorly drained soils (peaty gleys and peat) and this factor contributed principally to the large area deemed unsuitable for residue extraction. However, some soils are known to dry irreversibly under forestry, and to different degrees this is dependent on species. The soil wetness class assessment assumes no tree cover, and so the assessment presented here is the worst case. We would not advocate any adjustment to the classification, however, without obtaining further information.

The absence for the most part of any highly suitable areas was a result of the classification relating to soil fertility. Outside of Thetford (even on the chalk of the South Downs) there were very few soils with a pH value above 7 (in the surface soil). Furthermore pH values for Thetford, in excess of 7, may be anomalous, for data related to areas defined by the soil series. Data applied to the forest areas may in fact be derived from neighbouring agricultural land of the same soil series. We consider that the broad categories of soil fertility classes require further consideration. The pH 5-7 range is wide and the impact on soil fertility, following residue removal, will differ between the soils at either

end of this range. However, this dataset was developed originally to provide data to the Forestry Commission on soil fertility and tree growth.

The limitations imposed by the scale of the data, on which the models were based, meant that the approach adopted is not appropriate for the creation of a site management tool. Nonetheless we advocate national development of the model, to enable user-friendly investigation of forest residue availability within a selected radius of any grid reference. The advantage of scenario setting using digital models is that this development would be relatively straightforward. Some further research is needed to underpin the setting of threshold values for classifying site suitability for residue extraction. Inclusion within the model of yield prediction, for different tree species, and therefore of the associated residues, would be of considerable benefit to policy makers and to those proposing to invest in biomass energy generation.

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1 INTRODUCTION

1.1 Scope

In the UK, interest in the removal of forest residues has been stimulated by the possibility of using the biomass for energy generation. The UK Government's New and Renewable Energy policy was affirmed in the Energy White Paper 'Our energy future – creating a low carbon economy' (DTI, 2003). Biomass will play an important role in meeting the target of generating 10% of electricity from renewable energy by 2010. The use of woodfuel in the implementation of this policy could lead to the establishment of significant areas of energy crops in the UK and/or provide a market for small roundwood and forestry residues. However, there are potential environmental impacts associated with the removal of forest residues, in the UK. The principal of these are:

- sustainable forest productivity;
- protection of soil;
- maintenance of water quality, through the control of sediment transport;
- maintenance of bio-diversity;
- carbon sequestration; and
- woodland amenity and access.

A consistent approach to the assessment of environmental impacts of forest residue extraction was required which would enable the development and testing of scenarios. The approach adopted was the creation of geographic information system models.

1.2 Aims and objectives

The overall objective of this project was established in a project brief prepared by Future Energy Solutions (then known as ETSU) for the DTI. It was to assess the environmental implications of the shift in forestry operation and management practice necessary to supply significant quantities of fuel wood in the timeframe to 2020.

To this end, six objectives are to be met, as specified in the call for proposals:

- to review current forestry practices for the treatment of residues and the production of wood fuels and their impacts on air, land, water, flora and fauna, including soil and landscape (this is to be UK focussed, but will consider also experience and methods from other countries);
- to develop scenarios of how practices may change to develop and maintain sustainable supplies of forestry residues over a timeframe to 2020. This is to include an indication of the quantity of forestry land from which residues may be available;
- to consider how current environmental impacts may change as a result of the removal of forestry residues;
- to identify gaps in knowledge;
- to propose guidelines for the monitoring of a scheme that will test the conclusions of the report;
- the objectives will be met and reported in ways accessible to forestry professionals, environmental professionals, and the concerned layperson.

2 REVIEW OF CURRENT PRACTICES FOR TREATMENT OF FOREST RESIDUES

2.1 Literature review

2.1.1 Introduction

The potential environmental impacts of residue harvesting are, for the most part, considered to be negative in comparison with conventional stem-wood harvesting. The axiomatic requirement that harvesting systems be designed to minimise damage was formalised in the Helsinki Forestry Guidelines (Ministry of Agriculture and Forestry, Finland, 1993) and reinforced in the UK through a number of subsequent statements and guidelines, such as Forest and Water Guidelines (Forestry Commission, 1993) and the Forest Landscape Design Guidelines (Forestry Commission, 1994). These philosophies have been incorporated within the UK Forestry Standard and the UK Woodland Assurance Standard.

Adams *et al.* (2000) discussed the world-wide debate to define sustainable forestry. They affirmed the definition of sustainable forestry from the Helsinki conference *viz.* stewardship and use of forests, and forest lands, in a way and at a rate, that maintains their biodiversity, productivity, vitality, and potential to fulfil, now and in the future, ecological, economic and social functions, without damaging other ecosystems.

In the UK, high standards of environmental protection are achieved during mechanised forest operations by adhering to good practice guidelines, such as those mentioned above. The effectiveness of these guidelines relies on the judgement of harvesting managers and machine operators, whose considerations include:

- the scale of the harvesting;
- forest characteristics;
- ground conditions;
- machine specification; and
- extraction route layout.

The key consideration for harvesting managers is the use of small-diameter branch wood – brash – to create a protective mat over the soil, on which machinery travels. These mats reduce machine loads applied to the ground surface by spreading them over a larger surface area. Furthermore, direct contact between machinery and the soil surface is avoided, preserving the litter and organic soil layers, which help to protect the lower mineral layers.

The issues surrounding the removal of brash are therefore the primary potential environmental hazards of whole tree harvesting (WTH), for energy generators require that it should be clean of contaminating soil. Without the use of protective brash mats harvesting operations can result in:

- soil compaction;
- soil rutting; and
- erosion.

Whole-tree harvesting potentially compromises the principle of sustainable forest management if it leads to the removal of nutrients at a rate which exceeds return from weathering and atmospheric deposition. Furthermore, whilst removal of nutrients in brash material might result in a reduction in site fertility the mulching effect of brash in suppressing weed growth will be lost. In addition, there can be changes to the micro-climate (Proe *et al.*, 2001) and so site exposure, following WTH, may have an increasingly adverse effect on next rotation tree growth.

There are considered to be both positive and negative impacts of WTH on visual amenity and landscape, in comparison with conventional harvesting. In particular, the cleaner site left after WTH is preferable to some observers, but roadside brash stores may persist for many years and can be visually unattractive.

The removal of coarse woody material from a site will deprive the site of some niches for invertebrates and fungi. However, WTH has been conducted on numerous UK sites for the purpose of restoring forest land to other, non-forest, habitat types.

Factors influencing carbon sequestration by forest soils can be discussed in qualitative terms but quantified data are not available. Many forest soils have a high organic content and the removal of forest residues is at worst a carbon-neutral activity.

2.1.2 Impact assessment for forest harvesting

The soil-focussed work of Pyatt (1982) remains the basis of forest harvesting impact assessment in the UK. Pyatt (1982) described the susceptibility of forest soil types in the UK to ground damage by skidder operations. The categories may be applied similarly to forwarder working:

Risk Category	Soil Types
Low (under 'dry' site conditions)	Brown earths Podsols Rankers Skeletal soils Limestone soils Littoral soils (except with shallow water-table)
Medium (requiring restrictions to timing of operations and use of physical protective measures)	Shallow peaty soils (peat <0.45 m deep) Surface-water gleys Ground-water gleys Ironpan soils
High	Peatland soils (peat >0.45 m deep) Littoral soils with shallow water-table

Similarly, Pyatt (1982) identified two categories of soil types where fertility is either likely or unlikely to be compromised, in subsequent rotations, by WTH.

Risk Category	Soil Types
Low	Brown earths Surface-water gleys Ground-water gleys <i>Juncus</i> bogs
High	Podsols Ironpan soils Rankers Skeletal soils Littoral soils Unflushed peatland soils <i>Molinia</i> bogs Shallow peaty soils

2.1.3 Site productivity

Sverdrup and Rosen (1998) stressed the importance of including management of nutrient pools and fluxes within the concept of sustainable forest management. The measurement of the removal of nutrients in forest products is straightforward. However, prediction of the amounts of nutrients removed is complicated by variation according to tree species, harvest intensity and soil nutrient capital. It is the projection of the resulting permutations and combinations that have led to differing levels of concern regarding nutrient loss. Whilst Ovington (1962) calculated that the mean annual removal of nutrients in tree trunks is largely balanced by the input in precipitation, growing interest in WTH led to much early work of nutrient losses associated with different harvesting intensities.

Early concern was focussed on losses of N, which had been implicated in second-rotation decline in yield in intensively managed stands in the Southern Hemisphere. But in temperate forests of the Northern Hemisphere, assessments of extensive forest management demonstrates that N and S in atmospheric deposition is sufficient to compensate for that removed via stem-only harvest of mature stands.

Rolff and Ågren (1999) used a model of C and N fluxes to predict the effects of harvesting intensity in Norway spruce stands, at three levels of fertility. This was a response to concerns that simple input-output budgets do not take into account differences between total and available nutrients and that much uncertainty surrounds the flux of N, in particular. They predicted that, in Sweden, stands with higher productivity are less sensitive to intensive harvesting, partly because these stands occur in regions of high N deposition. The largest adverse impacts on productivity were from whole-tree thinnings and shortened rotation times. The model also indicated that increases in total biomass harvest were at the expense of stem harvest. In other words, there would be conflict between volume and value.

Field data from a clear cut site presented by Staaf and Olsson (1994) help to verify the model. They found that in comparison with WTH, conventional harvesting (CH) of a highly productive spruce site at Tönnersjöheden, Sweden resulted in significantly higher levels of NO_3^- , NH_4^+ and K^+ originating from logging residues in soil water below the rooting zone, during a 6-year period after cutting. Removal of residues reduced N leaching by up to 50 kg ha^{-1} over a 5-year period.

Concern over increased nutrient removal in WTH has focussed particularly on those macronutrients that are at low levels in atmospheric deposition, including P, K and Ca. Of these, removal of P is proportionally the greatest when WTH is compared to CH in Finnish forests (Mälkönen, 1976) and the north-eastern USA (Yanai, 1998). Yanai (1998) reported on the effect of WTH on P cycling, within a small catchment ecosystem at the Hubbard Brook Experimental Forest, New Hampshire. Whilst the data reported on the distribution of the macronutrients (N, P, K, Ca, Mg, S) are very thorough, it should be noted, however, that Grigal (2000) questioned the geographic representativeness of these data, particularly those relating to Ca, even within the context of the USA. The P content of branches and twigs was nearly twice that of stemwood and bark. These data do not appear to quite tally with the harvest removal ratios Yanai (1998) produced for WTH in comparison with conventional harvesting. The ratio was for a five-fold increase in P removal and a three- to four-fold increase in the removal of the other macronutrients.

The discrepancy can be explained because removal of biomass in the WTH plot was three times that of the CH plot and the total biomass harvested was very low by UK standards (50 t ha⁻¹ from a total pre-harvest above ground biomass of 133 t ha⁻¹).

On peatlands, both K and P are of similar concern (Grigal and Brooks, 1997, Teng *et al.*, 1997). Morris (1997) reported that K losses from WTH, on shallow soils in Ontario, might not be replaced over a rotation.

Sverdrup and Rosen (1989) used experimental lysimeter studies and Swedish forest survey soil analyses to calculate mass balances for the base cations Ca, Mg and K. They concluded that in 96% of productive forests, rates of weathering plus deposition were insufficient to support present rates of uptake by stem growth plus present leaching for one or more of the base cations. Even under a best-case scenario of lower pollution, present growth rates and 100 % efficiency in uptake, over at least 30 % of the total productive forest area removal would exceed supply. During 1983-85 the depletion rate was calculated to be, on average, 0.33 keq ha⁻¹ y⁻¹. Sverdrup and Rosen (1998) calculated that WTH, without base cation return, would significantly increase the depletion rate of base cations to 0.62 keq ha⁻¹ y⁻¹ and risk depletion of the soil in less than two rotations, almost anywhere in Sweden.

The high demand by some tree species for Ca has led to studies identifying its depletion by WTH at rates in excess of natural replacement (Federer *et al.*, 1989, Sverdrup and Rosen, 1998). Federer *et al.* (1989) demonstrated much greater losses of Ca than of other elements at six sites in the eastern US. Whilst WTH removed ≤ 3% of total ecosystem stores of P, K, Mg and that the proportion of N lost was somewhat greater at 4-8%, losses of Ca were as high as 13-19% of the ecosystem store. These values, in two oak and hickory forests, included increased losses in stream water and this mechanism was identified as being of particular importance for Ca.

Reynolds and Stevens (1998) produced a mass balance for Ca within a 50 year old Sitka spruce stand on acid, base-poor peaty podzol in upland Wales. They concluded that the whole crop will deplete soil Ca by 205 kg Ca ha⁻¹ – a mass approximately equivalent to the exchangeable Ca pool to the bottom of the B

horizon and equal to 14% of the total soil Ca reserve. WTH would remove 96%, that is 197 kg Ca ha⁻¹, whilst CH would remove 79 kg Ca ha⁻¹. Thus CH would allow 18 rotations before exhaustion of the total Ca reserve, whilst WTH would permit only 7 rotations (assuming that all sources of Ca were available equally to the crop). Yet measurements of exchangeable Ca by Reynolds and Stevens (1998) showed no differences between mature forest and acid grassland, suggesting possible errors in the mass balance. Nonetheless Reynolds and Stevens (1998) cautioned against WTH on acid, nutrient-poor soils, unless remedial measures are employed to supplement soil base cations.

Olsson *et al.* (1996) investigated harvest intensity on exchangeable cations in four coniferous forest soils in Sweden, but did not include the roles of leaching and nutrient assimilation. Effective CEC per unit area, pools of exchangeable K, Ca, Mg, Mn, Zn and total pools of exchangeable base cations were significantly lower after WTH than branch and stem harvesting or CH. A relatively high proportion of Ca left on site in the form of brash was recovered in the soil ca. 15 years after felling. Recovery was somewhat lower for Mg and only a small amount of K was recovered. In contrast, Knoepp and Swank (1997), studying stem only harvesting of mixed hardwoods in the southern Appalachians, USA, observed significant increases in soil exchangeable cations from 121 t ha⁻¹ logging residues, over a period of 17-20 years. Comparison with an adjacent reference watershed (using mean separation tests to consider differences between years) led Knoepp and Swank (1997) to believe that the increase in base cations may be long-lived.

Olsson *et al.* (1996) discussed fertilisation to compensate for loss of base cations at final felling and Olsson (1999) considered also compensatory fertilisation at first thinning. Harvesting of logging residues at first thinning had a small, non-significant negative effect on exchangeable pools of base cations. However, the investigations indicated differential impacts: WTH at thinning tended to affect K and Mg pools more than Ca pools whilst, at final felling, the negative effect on Ca (and to a lesser extent Mg) was more pronounced. K pools were affected both positively and negatively, but K tended to be lost from the soil profile. Fertilisation with N alone reduced base cations. No effect of compensatory fertilisation with N, P and K was detected.

However, Olsson (1999) cautioned that the slow release of Ca relative to K and Mg (and the relatively short term study) could provide an explanation for these results and that different results may be observed in the longer term.

The effects of harvest intensity identified by Olsson *et al.* (1996) were most pronounced in the uppermost horizons. In essence, the results demonstrate that residue harvesting has an acidifying effect on the soil. Furthermore, the issue of Ca depletion through harvesting is complicated also by its interaction with acidic deposition.

2.1.4 Acidification

Critical load is a quantitative estimate (based on current knowledge) of the exposure to an element above which it becomes a pollutant. The critical load is dependent on the sensitivity of the environment. Critical loads may be calculated with a combination of steady state and dynamic models based on critical chemical values for Al toxicity, the ratio of Al to Ca in soil solution, and ratios of NH_4^+ to K and Mg. A pan-European programme of intensive and continuous monitoring of forest ecosystems, implemented in 1994, has been reported by de Vries *et al.* (2002). They reported that in 30-39% of forest plots the ratio of Al:(Ca+Mg+K) in soils exceeded a critical value for Al toxicity of one. The concentration of potentially toxic Al in the subsoil was strongly correlated with the concentration of SO_4^{2-} and NO_3^- in soils with a base saturation below 25 % or a pH less than 4.5 (indicating that Al release is the dominant buffering process in acid forest soils). N inputs to 55% of the plots exceeded $1000 \text{ mol}_c \text{ ha}^{-1} \text{ y}^{-1}$ (equivalent to $14 \text{ kg N ha}^{-1} \text{ y}^{-1}$). Bobbink *et al.* (1998) considered that, at this concentration, species diversity of the ground vegetation of most forests would diminish. Bull *et al.* (2001) used critical loads and modelled deposition maps to report on the impacts of S and N deposition in the UK. They suggested that at the national level reduced impacts were expected by 2010, but highlighted a need for higher resolution deposition data and better estimates of NH_4^+ deposition in order to assess impacts on sensitive ecological sites, including woodland.

Availability of Ca from mineral weathering is difficult to assess (Kolka *et al.*, 1996) and, furthermore, Homann *et al.* (1992) suggested that forest type influenced weathering rate. Forest type has also been shown to influence the

rate of leaching losses (Eriksson and Jönsson, 1994). These complications, plus the difficulty of assessing dry deposition of Ca (Johnson and Lindberg, 1992), have encouraged spatial analysis of treatment areas and similar control areas.

Turvey and Smethurst (1994) related soil Ca and tree productivity but they noted also that its covariance with many other soil properties complicates the issue. Grigal (2000) commented that experimental manipulation to deplete soil Ca is difficult because of large soil pools and the affect on Ca-Al-pH interactions that can alter markedly soil chemistry. For this reason, additions of Ca associated with liming, often associated with a negative response do not provide information particularly valuable to Ca depletion.

2.1.5 Sediment and nutrient transport

Soil erosion is related to:

- soil properties, such as infiltration rate;
- topography, including slope length and steepness;
- rainfall, amount, intensity, and duration; and
- vegetation cover.

In a review of the efficacy of soil conservation practices in upland forestry in Scotland, Carling *et al.* (2001) report the division amongst authorities on the effects of harvesting operations on soil erosion in the UK: some considering soil losses to be minor and others significant. However, most of the publications cited date from the 1980s and early 1990s, which mean that the data reported were gathered largely prior to publication of documents on good practice such as the 'Soft Ground Harvesting Manual (Forestry Commission, 1991), the 'Forest and Water Guidelines' (Forestry Commission, 1993) and Forest Enterprise's 'Harvesting Manual' (Killer 1995).

Carling *et al.* (2001) cite an Environment Agency report of sediment yield increases for the Nant Tanllwyth and Hafren catchments in Wales, where felling took place in 10-15 ha plots, during 1996, following the good practice guidance referenced above. Sediment yield at Nant Tanllwyth increased from 240 kg ha⁻¹ in 1995 to 440 kg ha⁻¹ in 1996 following felling. In the Hafren

catchment the sediment losses were 160 kg ha⁻¹ and 230 kg ha⁻¹ in 1995 and 1996 respectively.

Hibbert (1967) recognised that clear-cutting has a variable effect on run-off that is difficult to predict. One of the adverse environmental impacts is the leaching of nitrogenous compounds and phosphate into surface water and groundwater. The main reason, reported by Rosen *et al.* (1996), for clearfelling causing increased leaching is that it leads to an increased mineralisation and reduction in nutrient uptake by biomass. The magnitude of the leaching depends upon site factors: mineralogy, hydrology, temperature and management history.

Rosen *et al.* (1996) compared runoff from 50% cleared and 95% cleared forest catchments with an unharvested control area; the increase over the control area was 85% and 110% respectively. Analysis of stream-water chemistry identified increased concentrations of K⁺, NH₄⁺, NO₃⁻, organic-N and total-N. Concentrations of H⁺ decreased. Changes in the concentrations of Ca²⁺, Mg²⁺, Na⁺, SO₄²⁻, and Cl⁻ were less distinct but, because the flow had approximately doubled following felling, there was a clear increase in the mass of ions transported.

Yanai (1998) compared particulate matter export from two catchments at Hubbard Brook Experimental Forest, one an undisturbed control, the other WTH. Sediment transport, in the first 3 years, was very variable but rose from an average 16 kg ha⁻¹ y⁻¹ (Std error = 7) to an average of 100 kg ha⁻¹ y⁻¹ (Std error = 67.6) following harvest. The amount of P exported was highly correlated with sediment transport, but the quantities remained small, at 0.18 kg ha⁻¹ over the three year period.

2.1.6 Carbon sequestration

The importance of forests as a carbon store is considerable. Forests have been estimated (Dixon *et al.*, 1994) to contain 1146 x 10¹⁵ g of the terrestrial C pool with two thirds of this (787 x 10¹⁵ g) in forest soils. This information may be compared with the estimates of Schimel (1995) to illustrate that forest soils contain an equivalent amount of C as the atmosphere (750 x 10¹⁵ g) and half the C in all soils (1580 x 10¹⁵ g). The significance of maintaining storage of C in

soils is amplified by comparison with Schimel's estimate for the store of C in all terrestrial vegetation, which is 610×10^{15} g.

Johnson and Curtis (2001) reviewed the literature on the effects of forest management on soil C and N. Based on 73 observations in 26 publications, they concluded that CH caused increases in soil C and N of 18% in coniferous forestry (but not in broadleaf or mixed stands), whilst WTH caused decreases of 6%. The data employed were for forests principally in North America but included Europe, North Africa and Australasia.

Time from harvest is an important variable in the assessment of the effect on C and N. Johnson and Curtis (2001) reported that, in several studies, CH led to an increase in soil C and N apparently through the incorporation of residues. This increase was sometimes short-lived (less than four years) whilst others observed the effect to be longer lasting (at least 18 years in the case of Knoepp and Swank (1997)). Black and Harden (1995) postulated that the key determinant of the duration of the positive impact was the initial C:N ratio of the soil. The incorporation of high C:N woody residues elevates soil C:N which decreases over time to the equilibrium level as soil C is selectively lost. Hyvönen *et al.* (2000) contributed to the many studies which relate organic matter decomposition rates to nutrient and lignin ratios. Others have considered decomposition rate by size fraction (for example, Pastor and Post, 1986). Kelsey and Harmon (1989) observed that bark decays more slowly than wood. Mattson *et al.* (1987) noted that its loss from twigs and branches was typically by fragmentation.

This suggests that leaving residues on site has no long-term positive effect on mineral soil C and so removal for energy generation may be desirable. However, the nutrients left on-site in residues may result in greater subsequent productivity, which would cause WTH to be less C efficient. Hyvönen *et al.* (2000) concluded that needles were the most important source of N (and P) during the establishment phase of the succeeding rotation. However, they concluded that, 15-20 years after clear-cutting, woody residues provided the majority of these nutrients.

2.1.7 Biodiversity

The impacts of brush removal across the food web have received relatively little attention. It is possible to postulate mechanisms by which biodiversity may theoretically be impacted.

For example, birds could be adversely affected by the unsustainable depletion of nutrients from a forest site. In the Netherlands, declining nesting success of the great tit has been attributed to thin egg shells (Graveland *et al.*, 1994). The egg shell defects are caused by calcium deficiency, due to scarcity of snails, whose shells were the main calcium source for the laying female. In this study, the cause of decline was elevated calcium leaching as a result of high levels of acidic deposition. Similar effects are theoretically possible as a result of nutrient withdrawal from sites in the removal of forest residues. Egg shell thinning is a useful potential measure of impact, as it has been documented elsewhere. For example, Green (1998) reports 7-10 % thinning of shells since 1850.

Other authors confine themselves to speculating on possible impacts based on broad understanding of woodland ecology. Nisbet *et al.* (1997) suggest that the removal of coarse woody debris associated with brush windrows and mats, left after typical conventional harvest operations, potentially deprives small vertebrates, invertebrates and fungi of important shelter, habitat and food source.

Data exist relating to a comparison of two sites in Sweden. Bengtsson *et al.* (1998) found that over the long-term (>10 years) the removal of harvest residues during WTH, had impacts on some parts of the food web but not on others. Predators (mites, spiders and predatory insects) were affected most severely with population reductions of between 30% and 60% compared to treatments where residues were retained on site. The effect was mixed among the detritivores-microbivores and fungivores, while no response was noted amongst the primary decomposers. The research did not consider the effects on groups higher in the food chain.

Diversity of ectomycorrhizal fungi has been studied in relation to nutrient levels. Diversity decreased significantly with elevated N additions (Brandrud

and Timmerman, 1998). Adams *et al.* (2000) cite a conference paper by Boerner and Sutherland (1995) in which they speculated that changes in N cycling could alter mycorrhizal functioning, with implications for tree species composition. However, Hagerburg and Wallander (2002) showed that intensive harvesting of forest residues did not affect the production of ectomycorrhizal mycelium in the forest soil under second-generation Norway spruce. Activity of micro-organisms offers potential for monitoring the function of forest soils following conventional or whole tree harvesting (Harris, 2003).

2.2 UK forest industry soundings

2.2.1 Introduction

During 2002 and the early part of 2003, a number of sites around the UK were visited and appraised, where, following timber harvesting, residues were also harvested. Residue removal was both for further exploitation, primarily energy production, or where habitat restoration required removal of the brash from site. Additionally, informal discussions were held with forest and timber harvesting managers in relation to this exercise. The sites visited and the observations recorded have been identified only in broad terms as some of those consulted were prepared to offer information and demonstrate file records that they wished to remain confidential.

The overall objective of this review was to develop a commentary about the environmental aspects related to the extraction of residues from timber harvesting sites. On-site review was based upon informal audit procedures for which the UK Woodland Assurance Standard (UKWAS) was used as the prime reference.

Specifically, discussions and site assessment focussed upon the following issues:

- preservation of forest productivity;
- protection of soil;
- maintenance of water quality, through the control of sediment transport;

- maintenance of bio-diversity and sustainable forestry management practice;
- carbon sequestration; and
- woodland amenity, access and conservation aspects.

2.2.2 Reference sites and key personnel interviewed

The sites visited included:

- North east England, including a Forestry Commission plantation where all small diameter material was being removed from site with the objective of providing both chipped and bundled material for energy production.
- South Wales, several sites where significant brash was accumulated on site and where this was causing major management problems in relation to restocking and the location of brash mounds.
- North Wales, a review of harvesting operations on Forestry Commission sites where particular attention had been paid to the management of brash accumulated from earlier harvesting operations.
- West Scotland, a number of privately owned sites, on moderately steep terrain, which had been harvested by skyline operations and where large amounts of brash had accumulated.
- South Scotland, where the management of brash for mats for extraction equipment was critical to the success or otherwise of the harvesting operations.

2.2.3 Review of site conditions

The site conditions found in UK forests are extremely variable and even within small geographic areas the variation can be considerable, which many forest managers pointed out as being a difficulty in setting a single standard for operational practices related to brash management. In many areas, the principal consideration had to be the management of forestry residues to provide brash mats suitable for extraction equipment. A secondary issue was the subsequent dispersal or treatment of brash to provide the optimal conditions for restocking.

The Forest and Water guidelines (Forestry Commission, 1993), which impose environmental safeguards on operational harvesting practice, provided an additional constraint.

The range of tree species available across the UK is considerable and this has an effect upon the potential further use of residues which forest managers can consider.

2.2.4 Market conditions

All the personnel interviewed recognised the influence of market conditions for timber and residues. Local markets were considered more important than national conditions and have a major influence on the exploitation of forest residues. The majority of harvesting managers conceded that they did not know a great deal about the market opportunities for residue disposal and where these existed locally the demand was generally too low to make its harvesting worthwhile.

Harvesting managers and the industry indicated that only residue material with a high wood content was sought after (that is material with a large percentage of green needle and other low grade content was not valued). Brash has a high level of this fine material and this was usually unacceptable to the limited market operating in this area.

2.2.5 Operational aspects

The opportunities to dispose of forest residues suffers, it was claimed, from the difficulty of reconciling cutting schedules, that have been designed to meet the needs of the existing timber market, with the needs of bioenergy producers. It was suggested that this could be resolved if merchantable timber were redefined to include residues, which would ensure that harvest planning incorporated the associated residue material. New long-term contracts for both timber and residues would need to be negotiated at the same time, but the relative value of the materials dictates that residues are of secondary importance.

In order that residue markets could operate efficiently, they would require that substantial quantities of suitable material were available to be worked in a short period. This could create its own difficulties, principally:

- stacking room,
- secondary handling of material on site,
- working time of non-dedicated, timber harvesting equipment on a lower value product and,
- logistics surrounding haulage on both forest and public roads.

Site management required a new and additional range of practices to be developed and access to appropriate and dedicated equipment, at a regional level. Machinery was considered to be a minor issue, but it was noted that suitable equipment would be expensive and that it was currently not readily available.

All managers interviewed indicated that the cost of residue removal from site was too high to making consideration of the practice justifiable. Similarly, purchasers usually wish the residue material to be left on site in an attempt to reduce moisture content. This presents its own set of difficulties in relation to suitable, convenient and sufficiently large storage areas adjacent to roads. The issue of economic operational activity was viewed as central. It was noted that forestry contractors operated at very tight margins and, if residue removal were to be developed, this factor would need to be researched further.

2.2.6 Issues in relation to the UK Woodland Assurance Standard

The following are observations made, by an approved assessor of the Institute of Environmental Management and Assessment, against the requirements of the Standard, based upon informal visits to twelve sites.

Compliance with the law

No observations were raised in respect of failing to comply with the law.

Planning

Paragraph 4.1.1 of the Standard states that “assessing, and taking into account, on and off site impacts is a requirement of planning forest operations”. In most of the examples visited this had been undertaken

inadequately. Many of those interviewed felt however that their planning reflected the paucity of current guidance on best operational practice for such schemes.

Forest plans were reviewed, for sites from which residues had been removed. For many, no reference was found to define the work carried out. This could be considered a minor non-conformance against UKWAS on the following grounds:

- no process to consider and record the impact on long-term productivity of the site and, therefore, on sustained yield;
- detailed documentary evidence of removals was not properly maintained in a number of cases;
- the implementation of the working plan for a number of areas had not been modified to note deviations and therefore justifying that all aspects had been taken into account to show that proper consideration had been made in relation to social and environmental aspects in particular;
- monitoring records of the removal of residues appeared to be poorly recorded to demonstrate management needs had been applied correctly; and
- in the longer-term, it will be essential to undertake appropriate monitoring of sites in relation to residue removal to meet other aspects, notably environmental issues.

On one major harvesting operation in the north of England, which incorporated removal of a significant fraction of forest residues, only limited consideration had been given to environmental planning. With hindsight the managers considered that their harvest planning should have taken into account the following:

- landscape implications;
- the retention of small grade material for a considerable period of time awaiting drying out and needle fall;
- possible crop health issues including insect population build up;
- potential effect on the nearby water course; and
- social impacts on the neighbours from intensive haulage activity during the short, but intensive, removal stage.

Assessment of environmental impacts

Paragraph 4.2.4 of the Standard states that “whole tree harvesting is not practised where it is likely to have significant negative effects”. The guidance section offers advice on this covering leaching, soil compaction and nutrient loss. Discussions with forest managers indicated again that little, if any, specific consideration had been given to these aspects during the planning stage. In only one case was any environmental monitoring being conducted: to quantify the local rabbit population.

- In few cases had the environmental impact of residue removal been assessed adequately. At one particular case study, in the West of Scotland, large amounts of brash had been harvested and accumulated at ride side. Subsequent removal did not happen for commercial reasons. Complaints had been received from the local community regarding adverse visual amenity impacts and for harbouring vermin. In this case, the brash had been on site for nearly five years with little, if any, deterioration.
- Similarly, in Wales several sites were visited where the brash had been harvested to roadside and not subsequently removed. This was in one locality adjacent to a water course. It was apparent that no consideration had been given to potential impacts on local water quality.
- The removal of all timber and lop and top from some sites may be at conflict with the requirement to provide deadwood habitats (paragraph 6.3.2) and no evidence was gathered to suggest that this aspect had been taken into account during the planning stages.

Forest protection and maintenance

In the case reviewed in the West of Scotland, where the brash pile had not been removed, the forest manager considered that it now constituted a serious fire risk, but that this had not been scoped in the estate fire plan.

The community

Generally, it was apparent that little, if any, consultation with interested parties had been carried out by the forest managers prior to operations. Issues of woodland access and the more intensive haulage requirements following residue harvesting had not been considered in most cases. Similarly, the

physical and environmental impacts created off-site on local roads had been neglected. However, a Haulage Code of Practice exists, which in part requires these issues to be addressed.

Forest Workforce

Some of the managers ventured the opinion that some of the operational practices utilised in the conversion of timber and materials for residue production did not fully meet current best practice in relation to health and safety aspects. Information supplied was no more specific and further verification by the assessor was not possible as visits were conducted following residue harvesting.

2.2.7 Summary

Many of the areas visited are now certified under the UK Woodland Assurance Standard, although at a number of these the harvesting of residues had occurred prior to the award of certification. The auditor considered that, had the harvested areas been audited against UKWAS, non-conformance reports would have been raised, generally of a minor nature.

It was apparent to the assessor that there is a base of knowledge developing within the UK forestry industry on the removal of residues. However, few of the forestry managers interviewed felt they possessed an in-depth knowledge of the implications of the operation, because individually the amount of work carried out has been limited to relatively small-scale schemes. Also there is reluctance amongst managers to pool and share the intimate knowledge they have developed. Some of those interviewed alluded to financial losses in residue harvesting exercises and a commercial imperative which prevented open discussion. The economic difficulties around residue harvesting have resulted in some reluctance to be involved further. The market opportunities were perceived to be very restricted.

A number of those interviewed indicated that they consider there is little clear and unambiguous information available on best practice and also what is necessary in environmental consideration requirements for the further development of residue removal.

3 SCENARIO SETTING

Scenario setting has been achieved at two scales. At a national scale it was necessary to consider the economic climate in which utilisation of the forest residue resource becomes viable. The second involved the creation of a GIS model that enabled consideration at the forest-scale of the suitability of residue extraction from a particular site, based upon variable environmental constraints and the need for sustainable forestry activity. The GIS approach will enable subsequent refinement, as more empirical data become available.

3.1 Economic considerations of forest residue harvesting

Energy generation from biomass is much more advanced in Scandinavia than in the UK. In Sweden and Finland wood-based energy contributes significantly to the countries' requirements: around 6% in Sweden (Miranda and Hale, 2001) and 15% in Finland (Malinen *et al.*, 2001). However, the figures are not directly comparable as the latter includes bioenergy from 'black liquor', a product of chemical processing of wood.

Miranda and Hale (2001) address the fundamental question of whether Sweden should continue to expand energy production from biomass. They recognise that without government intervention, decisions in energy investment would typically be driven almost exclusively by production costs, but they note also the complications created by issues of:

- energy self sufficiency;
- competitiveness in global commerce; and
- environmental considerations.

They attempted to address the possible expansion of bioenergy production by using full social cost analysis. However, the approach generates very wide cost ranges for oil and coal (and to a somewhat lesser extent for woodchips and refined wood fuels). They concede that most of the width of the ranges is driven by uncertainty surrounding placing financial values on environmental impacts. Their analysis suggests that, for Sweden, biomass energy would constitute a reasonable replacement for coal but that natural gas remains the

best economic and environmental solution. However, the authors acknowledge that incorporation of flue gas condensation technologies would enhance substantially the energy efficiency of wood chip combustion and deliver better environmental outcomes. The technology is designed to recover energy from steam during combustion of wood chips containing a high proportion of water.

Forsberg (2000) also recognised these issues but comes to a different conclusion. He did not accept the often-presented concern that transport of biomass (which is of low energy density) negates the advantages of using a renewable resource and cites recent lifecycle research from the USA, Sweden and Germany in which it was found that wood products compared favourably to coal. Forsberg (2000) compared environmental load profiles for specified long-distance handling chains between Scandinavia and Holland. He considered bioenergy transport in the form of:

- bales;
- pellets;
- tree sections; and
- transport of electricity via an international grid.

Pellet formation consumed considerable amounts of energy in drying which results in an unfavourable energy balance. However, this process might be possible using hot cooling water which was considered to be a loss. For the other biomass-based systems, delivering electricity was possible for a loss typically of 7-9% of delivered electrical energy. Forsberg concluded that long-range transport of biomass was possible without losing the environmental benefit.

Malinen *et al.* (2001) explained how in Finland, forest management models may be used to estimate energy-wood resources. They developed a system to enable the study of various energy wood cutting strategies and compared resource availability at two target generation prices. The model employed considered a number of feasible forest management schedules, including harvesting logging residues from spruce-dominated final felling sites, and determined cutting scenarios which optimised economically the division between energy-wood and industrial-roundwood. Significantly, whilst the

lower of the two production costs, used to determine the potential energy-wood harvest ($\text{€}2.10/\text{£}1.44 \text{ GJ}^{-1}$), was roughly equivalent to the price of industrial pulpwood ($\text{€}15.14/\text{£}10.35 \text{ m}^{-3}$) the authors consider that the higher generation cost level ($\text{€}2.57/\text{£}1.76 \text{ GJ}^{-1}$) was more realistic. It is important to note that these values (converted here from Finnish Markkaa, Feb 2004) relate to the production costs of the bioenergy residues and not to the cost of electricity generation.

Furthermore, the difficulty in establishing renewable-energy power stations, in the UK, has been highlighted by the failure of the ARBRE scheme in Yorkshire and by the refusal of planning permission for a biomass power station in Cricklade, Wiltshire. The new co-firing regulations may well help to overcome some of these constraints, especially in the vicinity of established solid fuel thermal power stations but currently most of the co-firing biomass is imported material (e.g. olive pips from Spain and Greece) or sewage sludge (Pooley, 2003). Pooley (2003) suggests that there are considerable technical difficulties to be overcome in producing suitable feedstock for coal-fired power stations from biomass and, further, that the result of the co-firing could be to depress other areas of renewable energy generation. However, it was announced in March 2004, that Drax Power Limited, Selby, Yorkshire is the first power station in the UK to use biomass (from short rotation willow coppice rather than forestry residues) in a co-firing application.

Drawing the economic case from the academic literature apparently demonstrates the need for a mechanism of financial support. Whilst progress is illustrated by the announcement on co-firing at Drax, the lack of market-pull, to encourage forest owners to market woody materials for biomass energy is also evident. However, the evolving policy environment may potentially transform the economic case, particularly EU policy to address climate change, to be implemented in 2005. Emission trading is central to the EU strategy to meet its climate change commitments under the Kyoto Protocol. The UK has already adopted this principle. The UK Emissions Trading Scheme (ETS) was launched in April 2002 as a voluntary, economy-wide, national-level system of trading in greenhouse gases (GHG). It was the first in the world and aims to allow businesses to reduce their emissions of greenhouse gases in the most economically efficient way. There were 32 organisations (“direct participants”)

in the scheme which voluntarily took on legally binding obligations to reduce their emissions against 1998-2000 levels. Compliance (met in the first year by 31 of the 32 direct participants) will deliver nearly 4 million tonnes of additional carbon dioxide equivalent emission reductions by 2006.

In addition, around 6000 companies have entered into Climate Change Agreements with Government, to set energy-related targets. Companies meeting their targets will receive an 80% discount from the Climate Change Levy, a tax on the business use of energy. These companies can use the scheme either to buy allowances to meet their targets, or to sell any over-achievement of their targets. Anyone can open an account on the registry to buy and sell allowances and, in the first year of the emissions trading scheme, 866 either bought allowances to meet their target, or sold surplus having reduced their emissions. Of 31,577,869 allowances which were allocated to companies, 7,216,105 had been transferred in the first year (DEFRA, 2003).

However, the EU Emissions Trading Directive will establish the world's largest emissions trading scheme when it begins to operate in 2005 and will signal the end of the UK ETS. EU ETS will be introduced in two phases. Phase 1 running from January 2005 to December 2007, will have lower penalties for non-compliance and provision of a mechanism to opt-out. Phase 2, will operate from January 2008 to December 2012, will have increased penalties and will be mandatory for all regulated installations. Banking of allowances between the two phases will not be permitted. The directive requires that the national governments allocate greenhouse gas emission allowances to five key sectors of the European economy. Eligibility was based on a sub-set of industries within Industrial Pollution Prevention and Control regulations and will operate similarly, that is a licence to operate and place conditions such as monitoring and reporting requirements. An estimated 1500 industrial installations in the UK will be covered by ETS and account for around 46 % of total CO₂ emissions *viz.* power, heat and steam generation; oil refineries; iron and steel production and processing; pulp, paper and board; and building materials. Only installations that have obtained permits prior to submission of the National Allocation Plan (NAP) to the European Commission, by 31 March 2004, will receive any allocation.

Having to purchase carbon allowances in order to comply with EU ETS would create a financial burden on UK companies but it is likely to give a boost for biomass fuels. The environmental benefits of substituting a renewable form of energy for fossil fuel are recognised in the guidance documents which accompany EU ETS: CO₂ emitted from the combustion of biomass will not contribute to the allocation. There does not appear to be any opportunity to receive financial incentive for soil carbon sequestration. Nonetheless there is now a clear incentive for operators of registered installations to switch to biomass fuels, including forest residues.

Carbon already has a market value. UK carbon trading appears to have stabilised at €12-13 (approximately £8.50, Feb 2004) t⁻¹ CO₂ (ENDS, 2004). A number of commentators (*e.g.* Jones, 2003 and Donovan, 2004) have indicated that there is the potential for carbon credit values to rise significantly and will become clearer when the NAP is finalised. An indication of the absolute maximum value that carbon credits might be expected to reach is the penalty for non-compliance, stipulated within the ETS Directive. The penalty in Phase 1 has been set at €40 (=£27.35, Feb 2004) t⁻¹ CO₂, rising to at €100 (=£68.38, Feb 2004) t⁻¹ CO₂ in Phase 2. However, a more informed view of values may be obtained by considering the allowance prices adopted within the Enviro European Carbon Balance Model (Donovan, 2004) which considers a trading range of £3-12 t⁻¹ CO₂. Donovan (2004) advanced three key factors which create current uncertainty over carbon prices:

- final details of the NAP of other EU member states;
- the extent to which central and eastern European countries are allowed to allocate emission reductions already achieved since 1990; and
- policy decisions that will affect the availability of project-based carbon credits within EU ETS.

Furthermore, there are overlaps between the Renewables Obligation and EU ETS which would provide biomass users with a potential “double benefit”. Biomass energy will generate a carbon allowance but continue to attract output based subsidy from Renewables Obligation Certificates. It appears that there is now a mechanism which can create significant business opportunities for UK forest residues within those key industrial sectors embraced by EU ETS.

Vertical integration of biomass energy, from forest residues, within forest owning/managing companies operating also in the pulp, paper and board sector has evident economic potential.

Donovan (2004) has modelled the gross financial impact of EU ETS to analyse the effect of percentage variation from a company's carbon budget in the period 2005-2010, assuming a constant market price of £10 t⁻¹ CO₂ over Phases 1 and 2 of the scheme. He estimated costs for percentage variance (accumulated linearly) for each of the sectors included in ETS. The impact of a 10% variation on carbon allocation for a pulp and paper installation, with a capacity of 400,000 t y⁻¹, would be £0.4m y⁻¹ in 2010. Over the five-year term of the analysis this represented a present value of £0.8m (discount rate not indicated). These sums could represent either shortfalls or positive cash-flows depending on whether the 10% variation in performance was negative or positive. In a commendably clear overview, Donovan (2004) also considered the historical prices for coal delivered to power stations. When he adjusted these to include a £10 t⁻¹ cost of carbon the fuel cost to deliver a unit of electricity oscillated narrowly around the equivalent cost supplied from biomass fuel at a constant, delivered value of £2 GJ⁻¹. The relatively pessimistic economic forecasts for biomass fuels, including forest residues, of only two or three years ago, do not adequately address the potential impact of carbon trading and integration of financial benefits of incorporating biomass into the energy requirements of high carbon emission companies.

3.2 Models as a basis for forward planning

Consideration of opportunities for removing harvesting residues from UK forests has been based to date on decision-support systems. Consideration by professional foresters of the opportunities on an individual site is, we believe, the most effective approach. It enables consideration of physical and chemical constraints alongside policy issues such as conservation management. However, to establish effective policy and appropriate economic drivers for energy generation from biomass requires directly comparable, nationally derived data.

At a national scale, digital models provide the flexible approach required to enable comparable assessment of geographic variability. However this approach has its limitations. Primary of these is the 1:250 000 coarse scale of the data on which the models are based. The importance of scale for the underlying data was tested by comparing outputs, for two of the sites, with data derived from 1:25 000 soil maps.

The processes on which a number of the parameters used in the model were based have been necessarily simplified. However, the advantage of a digital model is that it can be adapted readily when these parameters are refined. Future developments, in this respect are proposed at Section 7.3. It has been necessary also to divorce physical and chemical environmental constraints from the less tangible constraints imposed by local management, for biodiversity benefits, for example. The final concern is that the output of such models may be misused: because of the scale of the underlying data the output is not a substitute for professional local consideration of on-site opportunities. However, the parameters on which the models are based should, of course, all be part of the professional's on-site assessment.

3.3 Projection of practices to 2020

The information from the forestry industry plus our assessment of the policy environment provides the framework for projecting how practices will change to the year 2020. The industry soundings suggest that there are no great technical advances to be won to encourage residue recovery. The constraints are seen as being principally financial and logistical. Whilst the policy environment is moving more favourably toward biomass use for energy (particularly amongst high carbon emission industries) forest residues will still need to compete financially against other sources of biomass energy. Specific projections would not be possible without complete cycle economic analyses.

4 CREATION OF GIS MODELS

4.1 Selection of study sites

The selection of study areas embraced important afforested site types across the UK. The location of sites is presented in Figure 1. The area and type of forest cover for the seven case study areas are summarised in Table 1.

Table 1: Extent of forest cover within case study areas

Study area	Total area (ha)	Area coniferous woodland (ha)	Area broadleaf woodland (ha)	Total woodland area (ha)	% woodland area
Clashindarroch	40000	9449	295	9744	24.4
Morven and Aros	40000	7308	1504	8812	22.0
Southern Uplands	40000	7353	323	7676	19.2
Clocaenog	40000	6125	2977	9102	22.8
Thetford	40000	11881	4438	16319	40.8
South Downs	40000	1234	6671	7905	19.8
New Forest	40000	4273	12363	16636	41.6



Figure 1 Location of case study areas for modelling environmental impacts of the extraction of forest residues

Clashindarroch

The soils in this area of north east Scotland are predominantly podsollic and freely drained (humus-iron podsols and peaty podsols) developed on a range of parent materials derived primarily from acid metamorphic rocks. The dominant lithology is slate (accounting for approximately two thirds of the afforested area), with a much smaller area developed on drifts derived from schists. A wide range of other lithologies are also represented, albeit in much smaller extents, including acid igneous (granite), basic igneous (gabbro) and ultra-basic igneous (serpentine).

This area is representative of the soils and forestry of NE Scotland where traditionally Scots Pine was the favoured species, but in some areas, non-native coniferous species were increasingly introduced during the second half of the 20th century. In the National Inventory of Woodland and Trees (Grampian), Scots Pine is the single most extensive coniferous species, but is exceeded by the combined total of non-native conifers.

Morven and Aros

The soils and lithologies in this area are diverse. The single most extensive lithology is basalt, on which a relatively high proportion of forested sites (*ca* 42%) comprises free draining brown earths occurring on relatively steep slopes (*ca* 15-25°). Much of the remainder is a heterogeneous mix of soils with a strongly acid surface organic horizon, including peaty gleys, peat, peaty rankers and some peaty podsols. The landform is moderately undulating with frequent rock outcrops and most of the soils have poor or very poor natural drainage. In broad terms, these two contrasting site types are representative of much forestry in the western Highlands of Scotland.

Non-native coniferous species predominate, with Sitka Spruce most common, but with the likelihood that Lodgepole Pine will also be present over parts of the poorer site type. Larch will be a secondary component of the woodland on the better sites.

Southern Uplands

This area has a relatively uniform lithology (greywackes and shales), but with a diverse range of soils developed on them, representing to a large extent an

altitudinal zonation caused by different soil-forming conditions with increasing altitude. The physiography of the area is characteristic of the eastern Southern Uplands with deeply incised valleys and gulleys and predominantly convex non-rocky, smooth slopes (slopes decreasing with altitude). Brown forest soils are succeeded upslope by humus-iron podsoles which are subsequently succeeded by peaty podsoles. Peat has developed on the more gently sloping higher slopes and a small area of this is represented within the study area. Of the area under forestry, the brown earths comprise the largest proportion, indicative of the better growing conditions on these soils compared to those on the upper more exposed slopes.

Sitka spruce accounts for 69% of all coniferous forestry in the eastern Borders (National Inventory of Woodland and Trees (Grampian)), and in this area will be the dominant species. On the brown earths, there is likely to be some larch and Douglas Fir, and on the more heathery sites, some Scots Pine.

Clocaenog

Clocaenog forest, Clwyd is at the northern end of the Cambrian Mountains. The soils in and around the principal forest area are humic gleys on the summits, stagnopodsols on the shoulders of the hills, and podsollic brown soils on gullied and sheltered slopes. The stagnopodsols may feature a thin ironpan below an eluvial horizon or below a B_n horizon. If there has been no cultivation then a peaty surface layer is normal.

The variety of soil types has resulting in a mixed conifer forest with significant areas of broadleaves.

Thetford

The East Anglian Breckland is predominantly typical or calcaric sandy brown soils. The typical sandy brown soils are moderately or strongly acidic and show some signs of podsolisation below a superficial organic layer, but they lack the B_n and ochreous B horizons. The calcaric sandy brown soils occupy numerous small areas of the Breckland. The soils differ largely in the depth to a 'chalk-sand drift' forming the C horizon. In the calcaric form a calcareous C horizon is within 0.5 m depth.

The Breckland area was largely rough grazing or arable cropping until the 1920s when a large programme of afforestation began (by the newly created Forestry Commission). The principal species are Corsican and Scots pine, although a third of the area is afforested with broadleaved species. Although yields of unirrigated farm crops can be severely limited in dry years, the pines are not significantly affected by water shortage because they are able to draw reserves from the chalky substrate.

South Downs

Grey and brown rendzinas predominate in the cultivated land of the South Downs. Grey rendzinas are shallow or weakly developed soils and are extremely calcareous and evidently result mainly from degradation of former typical or brown rendzinas. Brown rendzinas have thin brown or reddish A and B horizons at or within 0.3 m of limestone or chalk.

Calciolous plant communities can be found in old grassland, scrub and woodland (particularly on the scarp face) where the soils are typical (humic) rendzinas. These soils are characterised by a thin very dark aggregated A_h (mull) and a brighter B horizon. Beech dominates semi-natural woods on these soils. It has also been planted widely, traditionally in association with a nurse crop of conifers. Tree performance is notably poorer than on deeper less calcareous brown soils nearby. Corsican and Austrian pine are the most successful of the conifers.

Colluvial rendzinas and stony colluvial soils are also found in the South Downs at the base of slopes. These are well drained soils. The latter are a sub-group of brown soils and are less calcareous than the former.

New Forest

Characteristic soils of the ancient deciduous woodland enclosures of the New Forest are non-humic luvic gley soils. An upper loamy or sandy eluvial horizon overlies an appreciably finer textured B horizon that is slowly permeable. The textural change can be very abrupt. The enclosures have been managed for timber and contain a number of broadleaf species, particularly areas of oak and beech. Holly is a common species in the understorey. Some areas of humus podsols in the New Forest have been afforested with pines. These soils commonly have thick E_a horizons and a relatively thin B_h horizon.

4.2 Model inputs

4.2.1 Analysis of Soil Datasets

Interrogation of the national soil inventory datasets for Scotland and for England and Wales revealed that, despite the high proportion of forest within the study areas, very few soil data points related to these afforested areas. The initial analysis of soil datasets tested separate approaches, in Scotland and in England and Wales, to increasing the number of point data available. In the three study areas in Scotland, soils of the same sub-group were identified, using all datapoints, not only those under woodland. The Scottish data related to the uppermost horizon, irrespective of the depth of that horizon. Initial analysis suggested that there were few large differences across land uses or soil subgroups. The latter is explicable because concentrations are considered per unit of weight of soil rather than by volume. The low bulk density of organic horizons means that these have a high nutrient content per unit weight of soil, but relatively lower amounts per unit volume.

The only clear effect of land use within soil sub-groups was expressed in the organic surface horizons under grassland, which had slightly lower C:N ratio than under moorland or woodland. Generally, however, the relationship between C:N and soil sub-group was strong. Mineral soils had values below 20, whereas soils with surface organic horizons are around 25. Base saturation was higher in mineral than in organic soils. Initial analysis of data suggested that values greater than or equal to 20% base saturation were observed only in mineral soils.

Soil data were obtained also for the case study areas in England and Wales and, as in Scotland, soil data were obtained for each national soil inventory datapoint, irrespective of land use. We tested whether it was possible to extend the number of data points on which analysis could be based. The subset of woodland points from the case study was used to interrogate the complete national dataset for woodland sites on the same soil series. In England and Wales all data were derived from a standard depth of 150 mm, irrespective of soil horizon.

Ultimately, a decision on the more effective approach to maximising reliably the number of soil datapoints used in the analysis was obviated by some mismatches between the datasets of Scotland and of England and Wales. The most significant differences were that C:N data were available only for soils in Scotland and extractable K data were available only for England and Wales.

4.2.2 Derived datasets

To avoid the difficulties described above from the use of original soil attributes, a number of derived datasets, common to both Scotland and England and Wales have been adopted. The derived datasets were all based on the published 1:250 000 scale soil maps. These were:

- Soil fertility for tree growth. A three class map, using soil pH as a surrogate for nutritional attributes such as base saturation and C:N ratio;
- Critical loads of acidity. A five class map, ranging from 0.2 kmol H⁺ ha⁻¹ year⁻¹ to >2.0 kmol H⁺ ha⁻¹ year⁻¹;
- Soil wetness class. A six class map incorporating soil moisture retention characteristics, integrated with the inherent dryness/wetness of the climate, expressed as field capacity days;
- Leaching potential. A two tier classification combining the permeability of the underlying lithology (three classes) with an appraisal of the leaching potential of the overlying soil;
- Erosion risk. A seventeen class map displaying inherent geomorphological risk of soil erosion assumed no vegetation and was abandoned in favour of a topographical approach.

4.2.3 Model attributes

Only physicochemical impacts associated with WTH can be modelled. Carbon sequestration and biodiversity impacts were excluded along with any other issues that may create the policy and management drivers behind decisions to harvest forest residues. For example, a decision based on conservation objectives to remove trees from afforested deep peats might take precedence over physical and chemical constraints that are important to the sustainable use of the site for forestry purposes. The datasets listed in Section 4.2.2 are directly linked to a specific environmental impact and these relationships are summarised in Table 2.

Table 2 Environmental impacts associated with forest residue removal and datasets used to assess their magnitude and location.

Dataset	Environmental impact
Soil fertility for tree growth	Unsustainable soil fertility
Critical loads of acidity	Acidification of soils and water
Soil Leaching potential and aquifer permeability	Eutrophication/enrichment of groundwater
Soil wetness class	Soil compaction
Digital Elevation Model	Soil erosion
	Transport of sediment to surface water

4.2.4 Land Cover data

Land cover data for Scotland was from the 1988 land cover survey of Scotland. Land cover for England and Wales was obtained from the Centre for Ecology and Hydrology land cover assessment 2000, which was derived from remotely sensed imagery. A combination of factors - the method by which land cover data were derived and the nature and scale of the afforested areas - meant that the maps of woodland cover in Scotland and in England and Wales were considerably different. The sites in England and Wales contained some large forest blocks, but also very many small fragmented areas of woodland whilst in Scotland forest cover was dominated by large plantation blocks. Only for the sites in Scotland therefore was it possible to isolate the forest areas within the mapped display. In England and Wales it was necessary to display modelled output for the entire 20 km x 20 km study area and visual assessment of the model output requires a separate accompanying map of the forest cover. The numerical data presented relate only to the forested areas.

4.3 GIS data structure

Data for the GIS analysis was in one of two forms – vector or raster. A vector data-structure holds the geometry of the mapped features as points, lines or areas, constructed from one or more closed lines (or polygons). Cartographically a vector data structure is precise. Attributes of the points, lines or polygons are stored within database tables that are linked to the files containing the geometry. A raster data-structure consists of a grid or array of

squares (pixels). The size of each square in the array is identical and determines the level of detail that can be represented by the raster. Smaller pixels give more precision than larger pixels. Each pixel has a single attribute value associated with it. Computationally, raster data is much easier to handle and therefore GIS packages use this format for many of their spatial analysis routines. Data for this research were received in both formats.

4.4 Justification of chosen impacts

4.4.1 Soil Fertility

Fisher and Binkley (2000) have suggested that there is no generally useful measure of forest soil fertility. Moffat (2003) agreed that there are no consistent soil variables which relate to tree growth and illustrated this by providing some examples of studies which have attempted to relate soil variables to productivity. The variables considered in these studies included:

- organic matter and C:N;
- soil type (major soil group) and parent material;
- clay content, drainage class, available water capacity and porosity;
- nutrient content, Exchangeable cations, P, N; and
- pH.

Soil pH is correlated with a number of important soil properties, such as C:N ratio, organic matter type (mor, moder or mull) and base saturation, and processes such as mineralisation, nutrient turnover, earthworm and biological activity, all of which influence the inherent fertility of the soil. However, Moffat (2003) noted that UK research shows that the relationship between pH and yield is less certain in forestry than it is in agriculture. Nonetheless, soil pH has been used as a surrogate attribute for this range of properties and processes within this project and a soil pH value has been attributed to each 1:250 000 scale soil map unit.

Soil fertility for tree growth relates fertility to pH, reflecting the positive relationship between mineralisation, base saturation and soil fertility. The data are provided as a 1 km point grid. The dataset was produced originally for use by the Forestry Commission.

4.4.2 Critical Load

The critical load concept originated in Canada during the early 1970s and is defined as 'a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified elements of the environment do not occur according to present knowledge' (Nilsson and Grennfelt, 1988). Soils therefore should be protected from long-term change due to anthropogenic inputs which cannot be compensated by natural soil processes.

The chemical weathering of minerals is considered to be the single most important factor determining critical loads for forest soils. Five soil classes (often referred to as Skokloster classes) have been derived based on their dominant weatherable materials (Hornung *et al.*, 1995). Critical loads of acid inputs were assigned to each of these classes; the more base-rich the soil material, the higher the critical load. Therefore, soils developed on acid parent materials, within which the dominant minerals are quartz and K-feldspar, for example, have very low critical loads ($< 0.2 \text{ kmol}_c \text{ H}^+ \text{ ha}^{-1} \text{ year}^{-1}$). In contrast, base rich soils have much higher critical loads of acidity ($> 2 \text{ kmol}_c \text{ H}^+ \text{ ha}^{-1} \text{ year}^{-1}$) before environmental damage is predicted to occur. Other soil attributes, for example soil pH or drainage class, can reduce or increase the critical load; freely drained soils and shallow soils have a lower critical load than soils with impeded drainage or soils developed on deeper parent material.

4.4.3 Nutrient leaching

Nutrients from decomposing forest residues left on site may potentially leach to groundwater. A number of soil properties influence the downward passage of water through the soil profile and the attenuation of contaminants which this water, or any other liquid, may contain. These properties include texture, structure, soil water regime and the presence of specific layers, for example an organic surface horizon, within the profile. Three classes of soil leaching potential – high, intermediate and low - have been identified. The high and intermediate classes have been separated into three and two subclasses respectively. Each soil map unit in the 1:250 000 scale soil map has been classified into a soil leaching potential class, based on the properties of the component soil(s) within them (Palmer *et al.*, 1995).

Geological formations vary in their hydraulic properties and flow through them can be classified as fracture, inter-granular or a combination of the two. Each geological formation has been classified based on the permeability characteristics of the unsaturated zone of the uppermost formation. Three classes, highly permeable, moderately permeable and weakly permeable, have been identified and a map produced indicating their extent and distribution (Palmer *et al.*, 1995).

Data were extracted from the datasets for the case study sites only for the following combinations.

Aquifer Permeability	Soil Leaching Potential
High	High
High	Intermediate
Moderate	High

In these circumstances extraction of residues has potential environmental benefits and cannot be considered in the same way as the other potentially negative impacts.

4.4.4 Soil Compaction

The risk of soil compaction (and rutting) is based on soil wetness class. The risk of damage to soils from trafficking by machines is much higher if the soils are wet. An assessment system to determine soil wetness has been devised (Thomasson, 1982) which incorporates soil attributes which influence the moisture retention capacity of the soil and the wetness of the climate in which different soils are found. In this way, different soils within the same climatic context are distinguished and, similarly, the system discriminates between soils of comparable properties, but within different climate regimes.

The soil attributes used are the presence of gley features at specific depths within the soil profile, the depth to an impermeable horizon and the retained water capacity of the topsoil. The influence of climate is assessed using median annual values of field capacity days, in essence a measure of the relative wetness of the climate across the country.

Soil maps and attribute data have been analysed, interpreted and integrated with the number of days at field capacity dataset to produce a wetness class map for Great Britain (for example, in Scotland, Lilly and Matthews, 1993). One of the main benefits of its use in this project was that different soil-climate interactions across the country were assessed in an integrated appraisal rather than dealing separately with soil and climatic influences.

Some soils are known to dry irreversibly under forestry, and to different degrees this is dependent on species. The soil wetness class assessment assumes no tree cover, and so the assessment presented would be for the worst case. We considered however that in the absence of any further information no adjustment to the classification could be justified.

4.4.5 Soil Erosion

Erosion of forest soils may occur by surface removal or by landslip of a mass of unstable soil. Surface erosion is a function of the following site factors:

- slope angle and length;
- rainfall intensity and duration;
- soil properties (such as infiltration rate); and
- vegetation and soil cover.

Vehicle movements during harvesting operations may damage soils by rutting or result in the localised loss of surface litter or the upper soil horizon. These actions may create a key from which erosion of soils is initiated. Slope angle is a vital factor in assessing the risk of subsequent soil erosion from this initial focus. Hence, the suitability of residue removal from a site diminishes with increasing slope angle. However, when slopes are too steep for trafficking (and alternative harvesting mechanisms are employed) then the damage to soil that can create the trigger for erosion is avoided. There is no quantified guidance on safe working on slopes (because micro-topography is very important) but a slope angle $>25^\circ$ was selected as one on which there would be no harvesting traffic. Hence these slopes are unclassified in the impact assessment.

4.4.6 Sediment transport to watercourses

Soil erosion has adverse impacts on the site itself and from the transport of eroded material to watercourses. The additional risk posed by soil erosion, in the vicinity of watercourses, is universally acknowledged in UK forestry. Hence, the potential impact of soil erosion to watercourses has been acknowledged by considering slope angle of land, within 100 m of watercourses, as an additional risk.

4.5 Impact thresholds

Thresholds for each data layer have been selected, representing an assessment of each individual impact expressed in terms of suitability for forest residue extraction. These are presented in Table 3. In practice the terms highly, moderately and marginally suitable may refer to the likely degree of impact or to differing periods of time in which site conditions permit residue extraction. However, these should not be translated into time periods because of the degree of annual variation. The term unsuitable is applied to those areas when typically there is no opportunity during the year to traffic the soils without environmental damage or at a very limited number of sites which have an exceptionally high acidification risk.

Harvesting of residues which have been used as brushmats and trafficked is not a realistic prospect because of soil contamination. Currently, the model is insufficiently sophisticated to enable division between non-harvested brushmat material and surplus harvestable residues. Thus, the model considers only sites in terms of impacts upon sites from harvesting with or without the use of brushmats. This is a major weakness of the model. At some sites removal of some of the residues, whilst the remainder form brush mats, is possible technically (although the economics requires further detailed assessment).

4.5.1 Sustainable soil fertility

The thresholds for sustainable soil fertility are those set by the Forestry Commission dataset. It has been suggested that the thresholds present too coarse a measure because soils of $\text{pH} < 5$ are all bracketed into a category which suggests that they may be vulnerable to a loss of nutrients in brush. Evidence from the Forestry Commission's Biodiversity Assessment Project (Humphreys, *et al.*, 2003), involved the detailed UK-wide survey of 52 forest plots covering

broadleaf and conifer species and various growth stages (pre-thicket, mid-rotation, mature and over-mature). The minimum, mean and maximum pH values were respectively 3.3, 4.1 and 5.3 to 0.05 m depth and 3.6, 4.3 and 7.9 in the 0.05 - 0.1 m layer. Evidently, there are few forest soils above pH 5 and a lower threshold of pH 4 may indeed have been preferable. However, given the restrictions imposed by an existing dataset it would be imprudent to adopt anything other than a precautionary approach, particularly as demonstrating measurable on-site impacts will prove so difficult (see Section 7.3.1). Research evidence within the review of literature on site fertility and the strictures of demonstrating sustainable forestry currently make the sites only 'marginally suitable' for residue harvesting *relative to* retention of the residues post harvest.

Table 3: Classification thresholds for site suitability for forest residue removal

Environmental Impact	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable (S4)
Unsustainable soil fertility	Topsoil pH >7	Topsoil pH 5-7	Topsoil pH < 5	
Acidification of soils and water	Critical load > 1.0 kmol H ⁺ ha ⁻¹ year ⁻¹	Critical load 0.5-1.0 kmol H ⁺ ha ⁻¹ year ⁻¹	Critical load 0.2-0.5 kmol H ⁺ ha ⁻¹ year ⁻¹	Critical load <0.2 kmol H ⁺ ha ⁻¹ year ⁻¹
Eutrophication/enrichment of groundwater	Potentially beneficial and therefore not classified in this way.			
Soil compaction	Soil wetness classes I and II	Soil wetness class III	Soil wetness class IV	Soil wetness classes V and VI
Soil Erosion	Slope < 5°	Slope 5° <10°	Slope 10° <25°	
Transport of sediment to surface waters	Explanation provided in text below			

In addition, it has been suggested that soils of pH>7 are at risk of lime-induced chlorosis. Indeed, this may be so but broadly we considered that the additional risk associated with the removal of brash was inconsequential. This reflects the fact that the model is not an absolute assessment but considers environmental impacts relative to the *status quo*, that is brash retention on site. We should emphasise again that the model cannot consider wider (off-site) benefits to sustainable development, from the adoption of renewable energy from forest residues, which may outweigh negative on-site impacts.

4.5.2 Soil erosion risk

The assessment of erosion risk is based on topography, but assumes that erosion will be initiated from a key, created by vehicle movements during harvesting operations. Digital elevation models (DEMs) were available for each study site as a 50 m raster dataset. Geographical Information System (GIS) software was used to generate slope rasters, measured in degrees. There is no established basis for differentiation between slope classes.

For example, health and safety guidance is not prescriptive by slope angle, but requires operator decision making, which takes into consideration surface roughness in addition to mean slope angle. For this assessment, to which the impact of vehicle movements is central, slopes greater than 25° have not been classified; it has been assumed that cable crane or skyline harvesting systems will be employed and there would be minimal ground disturbance.

4.5.3 Threshold derivation for sediment transport to watercourses

As for erosion risk, digital elevation models (DEMs) were used to generate slope rasters, measured in degrees. For the risk posed from transport of sediment to watercourses, the limitation on slope angle was not applied. The erosive powers of converging flows to watercourses may be sufficient to initiate erosion processes and slope angles greater than 25° have not been incorporated into the classification.

Transport of eroded soil to watercourses was derived from the slope characteristics adjacent to the channel. The drainage network was derived using the DEMs. Four 'buffer zones' around the drainage network were created; these were at 75 m and 125 m distances on both the left and right side

of the channel (Figure 2). The original DEM was converted to a point grid and the points 50 m and 100 m from the river channel were extracted by overlaying the 4 buffers. This resulted in the production of 5 point coverages.

- Points where grid cells are intersected by the drainage channel,
- Points 50 m to the left and right of the channel, and
- Points 100 m to the left and right of the channel.

The need to create broader buffers, at 75 m and 125m from the drainage channels (instead of 50 m and 100 m), was due to the convoluted shape of the network. Inclusion of points at 50 m distance from an adjacent cell would have resulted in many missing points.

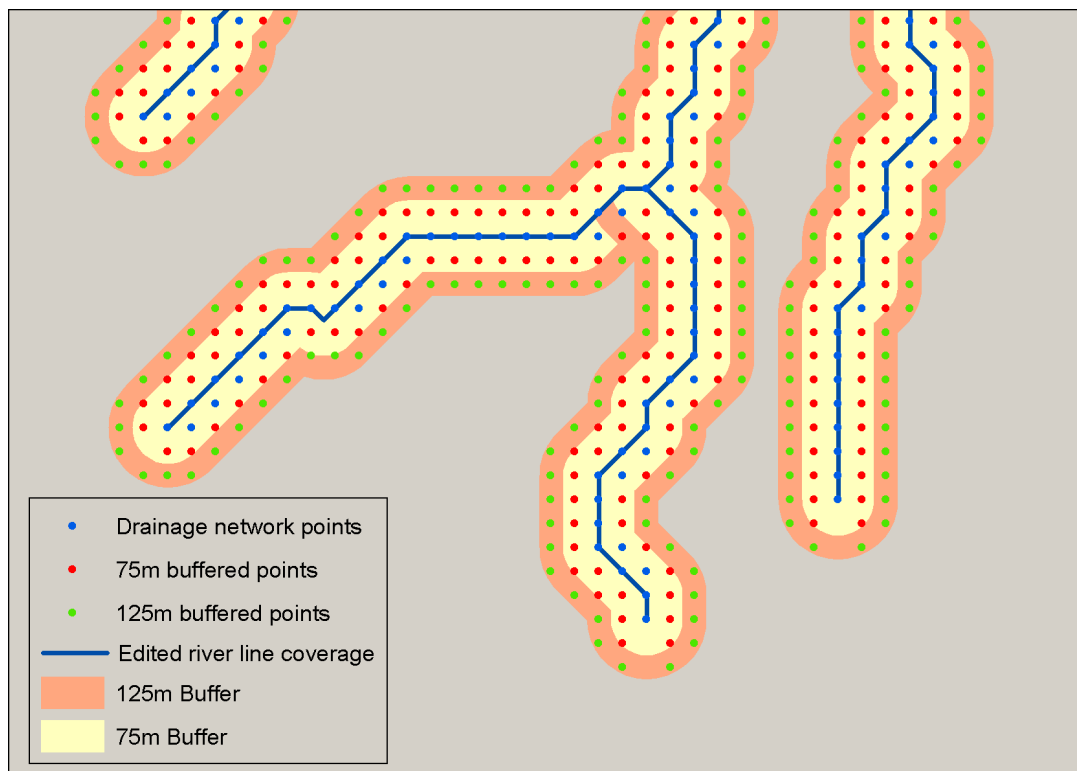


Figure 2 Creation of datapoints around a drainage network

For each point surrounding the drainage network the slope value was extracted. These values were used to generate suitability for eroded soil transport for the areas to the left and right of the channel cell. The value given to the channel and its buffer zone is an average of the left and right values.

Table 4 demonstrates how the erosion transport value is derived from the slope values:

Table 4: Derivation of classes for sediment transport to watercourses based on slope values adjacent to the channel

Mean slope angle (°) at distances 0-50 m from channel	Mean slope angle (°) at distances 50-100 m from channel	Output class for sediment transport, applicable to area bounded to 100 m on each side of channel
< 5	< 5	1
< 5	5 < 10	1
< 5	10 < 25	2
5 < 10	< 5	2
5 < 10	5 < 10	2
5 < 10	10 < 25	3
10 < 25	< 5	3
10 < 25	5 < 10	3
10 < 25	10 < 25	4
> 0	> 25	4
> 25	> 0	4

For this variable all areas beyond 100 m of a drainage channel are unclassified and assigned a value of 0. For the area, 200 m wide, defined by a channel, the model assigned a single average value of the two channel sides. Non-integers were rounded up to reflect conditions of the steeper slope (Table 5).

Table 5: Allocation of suitability classes for sediment transport to watercourses, based on the mean, of slope output, for the two sides of the channel

Mean output class derived for sediment transport	Output in terms of modelled suitability classification
1	Highly suitable (S1)
1.5	Moderately suitable (S2)
2	Moderately suitable (S2)
2.5	Marginally suitable (S3)
3	Marginally suitable (S3)
3.5	Unsuitable (S4)
4	Unsuitable (S4)
Beyond 100 m of a channel (not applicable)	Unclassified

4.5.4 Re-classification of dataset outputs

A number of possibilities exist for the display of the modelled output. It would have been possible, for example, to adopt the lowest suitability class presented at each point. However, this would result in a serious loss of information to the user.

Outputs from each of the above datasets were reclassified in order to create an overall suitability classification output using combined values. However, it was necessary to avoid giving the impression that this provides a numerically-based system in which summed numbers are related directly to the suitability of removing residues. It is not a numerical system of relative suitability; the numbers serve only as working labels and may be adjusted to text in the final output product. To help avoid confusion surrounding the use of numerical coding, and to maximise the ease with which information could be displayed, significantly different values were employed for each suitability class. This approach enables individual factors behind suitability classes to be considered.

The table below shows the re-classification values:

Input grid value	Output re-classified value
S1	1
S2	10
S3	100
S4	1000

It is possible to derive the same numerical output through combination of a variety of environmental impacts. The models enable each of the combinations (and the areas represented by them) to be considered separately, as for example in the screen image in Figure 3. Identical numerical codes can be shared between different combinations of environmental impacts. For the purposes of this project, however, individual suitability classes were not required. This detail of output would be of value only if the models were developed as a management decision-aiding tool.

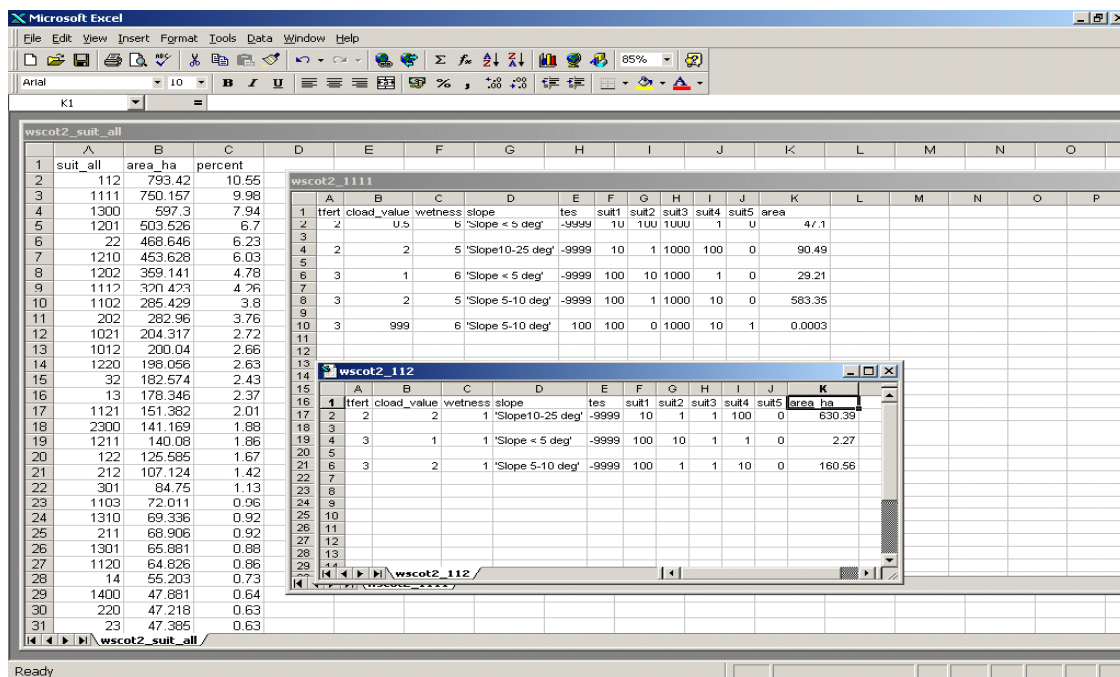


Figure 3: Example of database output available for any forest area

This logarithmic numbering system has been applied only to the adverse environmental impacts of forestry residue removal. The need to avoid the view that this is a cumulative numerical system requires a different approach to the potentially positive impact of reducing leaching to groundwater. This impact should not be viewed as a reduction in a 'total score' of adverse impacts. Hence, its display is by hatching on the output maps and provides simply another layer of information for the user.

The level of detail provided in the output maps aims to reinforce the fact that the models outputs do not provide a 'score'. We have resisted the inclusion of a step within the model in which accumulated impacts are then reassessed. The overall suitability classes, for moderate and marginal, were sub-divided only to indicate how many of the impact criteria fell within these categories. It must be recognised that a site that is moderately suitable for residue harvesting on a number of criteria may in fact be only marginally suitable overall. Similarly, a site that was considered marginally suitable for residue harvesting, on a number of criteria, could be deemed unsuitable overall, but this decision should be made only by the user and is not a function of the model. The model outputs have been presented in a manner which maximises the information available to the user whilst remaining comprehensible in terms of the number of suitability classes. This is both appropriate for this study and should the system ever be developed as a decision-support tool, access to untransformed data will still be required.

5 MODELLED ENVIRONMENTAL IMPACTS

The modelled outputs are presented for each case study area in an accompanying maps document. Some maps have been replicated, for illustrative purposes, in this report, but the complete set of maps has been bound separately to ease cross reference between the modelled output and its descriptive analysis. Because of the scattered nature of woodland cover, in the study areas in England and Wales, it was not possible to display outputs only for areas of woodland: they have been displayed for the complete 400 km² study area alongside a map of broadleaf and coniferous tree cover. Each of the environmental impacts has been presented individually, expressed in terms of impact on the suitability for forest residue harvesting. The principal mapped outputs are of the accumulated impacts. These have divided the study sites into areas of high, moderate or marginal suitability for residue extraction and identified unsuitable areas. Further sub-division, according to the number of impacts rated moderate and marginal have been displayed separately: division of the highly suitable areas is not possible and the exercise serves no purpose for areas deemed unsuitable. All modelled outputs of suitability classes for residue extraction based on individual environmental impacts, and for suitability based on cumulative impacts, are contained within the separate maps document.

5.1 Soil fertility

Because of its relatively coarse resolution, soil fertility varies relatively little across the case study sites. This is exemplified by the data for Clocaenog, where soils are almost entirely below pH 5 (Figure 4) and would be vulnerable to a loss of nutrients in brash, because the soils have poor capability to supply base cations and a low mineralisation capacity. Conversely, the model identifies very little risk from a loss of soil fertility in the majority of high pH, calcareous soils of the South Downs (Figure 5).

Figure 4: Suitability classification for residue extraction at Clocaenog, based on soil fertility for tree growth

Figure 5: Suitability classification for residue extraction in the South Downs, based on soil fertility for tree growth

The proportions of the afforested areas that fell into the various suitability classes are listed in Table 6, below.

Table 6: Proportion of forest area suitable for forest residue harvesting based on the risk this poses for decreased soil fertility

Study Area	Suitability assessment based on impact of nutrient removal			
	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable (S4)
Clashindarroch	0.000	0.602	0.398	n/a
Morven and Aros	0.000	0.369	0.631	n/a
Southern Uplands	0.000	0.688	0.312	n/a
Clocaenog	0.000	0.000	1.000	n/a
Thetford	0.331	0.577	0.092	n/a
South Downs	0.204	0.630	0.165	n/a
New Forest	0.002	0.707	0.291	n/a

5.2 Critical loads

Soil maps and attribute data have been analysed and interpreted to produce a critical loads map for the UK (Hornung *et al.*, 1995) and this was the basis for the assessment of the suitability of different forest soils for residue removal in this project. The datasets for critical loads, like soil fertility, differentiate between the poorly buffered, coarse textured Breckland soils (Figure 6) and, for example, the base rich soils of the New Forest, (Figure 7).

Figure 6: Suitability classification for residue extraction in Thetford, based on critical loads of acidity.

Figure 7: Suitability classification for residue extraction in the New Forest, based on critical loads of acidity.

The proportions of the afforested areas that fell into the various suitability classes are listed in Table 7 below.

Table 7: Proportion of forest area suitable for forest residue harvesting based on the risk this poses for increased site acidification

Study Area	Suitability assessment based on critical load			
	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable (S4)
Clashindarroch	0.213	0.047	0.740	0.000
Morven and Aros	0.617	0.044	0.338	0.000
Southern Uplands	0.009	0.006	0.938	0.046
Clocaenog	0.169	0.088	0.743	0.000
Thetford	0.347	0.000	0.561	0.092
South Downs	0.736	0.140	0.029	0.094
New Forest	0.059	0.790	0.001	0.150

5.3 Soil compaction

Wetness class provides a major constraint to harvesting of residues in areas of upland forestry as evidenced from the example from Morven and Aros (Figure 8). The importance of soil type in influencing wetness class and hence compaction risk is observed most noticeably in the New Forest where the risks are significantly greater on the gley soils (Figure 9).

Figure 8: Suitability classification for residue extraction in Morven and Aros, based on soil wetness class.

Figure 9: Suitability classification for residue extraction in the New Forest, based on soil wetness class.

The proportions of the afforested areas that fell into the various suitability classes are listed in Table 8 below.

Table 8: Proportion of forest area suitable for forest residue harvesting based on the risk this poses for increased soil compaction

Study Area	Suitability assessment based on likelihood of soil compaction			
	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable (S4)
Clashindarroch	0.546	0.034	0.320	0.100
Morven and Aros	0.404	0.000	0.030	0.566
Southern Uplands	0.770	0.000	0.174	0.056
Clocaenog	0.448	0.130	0.422	0.000
Thetford	0.997	0.003	0.000	0.000
South Downs	0.918	0.082	0.000	0.000
New Forest	0.298	0.702	0.000	0.000

5.4 Soil erosion

A relatively simplistic approach was adopted to determine of the risk of soil erosion, based solely on topography. A slope map was generated from a 50 m Digital Elevation Model (DEM) and aggregated into the slope ranges as outlined in Section 4.5. The magnitude of the impact was greater in the upland forestry sites in Scotland (Figure 10) than in the lowlands of England, such as the South Downs (Figure 11). The erosion risk was considered to be dependent on initial disturbance to the forest floor, by trafficking, from which the problem would develop. Hence, there are no data for the steepest slopes, on which vehicle movements are not possible.

Figure 10: Suitability classification for residue extraction in the Southern Uplands, based on topographical assessment of erosion risk.

Figure 11: Suitability classification for residue extraction in the South Downs, based on topographical assessment of erosion risk.

The proportions of the afforested areas that fell into the various suitability classes are listed in Table 9 below.

Table 9: Proportion of forest area suitable for forest residue harvesting based on the risk this poses for increased soil erosion

Study Area	Suitability assessment based on soil erosion risk			
	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable (S4)
Clashindarroch	0.256	0.400	0.344	n/a
Morven and Aros	0.222	0.403	0.375	n/a
Southern Uplands	0.078	0.252	0.670	n/a
Clocaenog	0.406	0.338	0.256	n/a
Thetford	0.999	0.001	0.000	n/a
South Downs	0.530	0.301	0.168	n/a
New Forest	0.925	0.074	0.001	n/a

5.5 Transport of sediment to watercourses

An assessment of the additional erosion risk posed by transport of eroded soil to watercourses was derived from the slope characteristics adjacent to drainage channels. Depending on the combination of slope values in each, a suitability classification was derived for each 50 m length of channel to a distance of 100 m from the channel (described in Section 4.5). Hence, the significance of this environmental impact in each of the case study areas is a function of topography, within 100 m of watercourses and drainage channels. This means that 70-80% of the case study areas receive no classification for this impact (Table 10).

Table 10: Proportion of forest area suitable for forest residue harvesting based on the risk this poses for transport of sediment to watercourses

Study Area	Suitability assessment based on sediment transport risk				
	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable (S4)	Unclassified
Clashindarroch	0.061	0.066	0.027	0.078	0.768
Morven and Aros	0.079	0.102	0.046	0.114	0.668
Southern Uplands	0.023	0.038	0.031	0.194	0.715
Clocaenog	0.125	0.071	0.043	0.067	0.694
Thetford	0.226	0.000	0.000	0.000	0.774
South Downs	0.186	0.067	0.025	0.018	0.705
New Forest	0.268	0.005	0.000	0.000	0.727

As the drainage network was derived from the DEM, it is possible that some of the channels may not be a permanent part of the drainage network. Nevertheless they are part of the same network and eroded soil from adjacent slopes is at risk of reaching a water course, particularly during a storm event.

5.6 Nutrient leaching to groundwater

The calcareous soils of the South Downs and the Breckland soils of Thetford Forest both possess considerable areas of soils of high leaching potential overlaying permeable geology (for example, Figure 12).

Figure 12: Classification of risk for eutrophication of ground water for Thetford.

In these areas, leaching of nutrients to groundwater from brash remaining on site following conventional harvesting poses an environmental risk which could be removed or reduced by whole tree harvesting. Ordinarily, however, the risk from nutrient release from gradual decomposition of residues is insufficiently serious to affect conventional forestry harvesting practice and the benefits should be considered in this context. The risks of nutrient leaching to groundwater in the sites in Scotland, at Clocaenog and the New Forest are in Wales and the sites in Scotland are insignificant.

Major or moderate permeability in combination with high or intermediate leaching potential were considered to benefit potentially by removing forest residues, and with it the risk of materials leaching from it to groundwater. The proportions of the case study sites that fell into the higher risk classes are listed in Table 11, below.

Table 11: Proportion of forested areas within the case study sites from which forest residue harvesting may reduce the risk of materials leaching to groundwater

Study Area	Major permeability and high leaching potential	Major permeability and intermediate leaching potential	Moderate permeability and high leaching potential	Unclassified (other possible combinations of permeability and leaching potentials)
Clashindarroch	0.000	0.000	0.030	0.970
Morven and Aros	0.000	0.000	0.012	0.988
Southern Uplands	0.000	0.000	0.050	0.950
Clocaenog	0.002	0.037	0.004	0.956
Thetford	0.900	0.095	0.000	0.005
South Downs	0.709	0.125	0.057	0.109
New Forest	0.000	0.000	0.109	0.891

5.7 Overall suitability classification for forest residue harvesting

Table 12 summarises combined suitability classes for forest residue harvesting, at the seven case study sites. We are cautious about presenting classes of suitability based on cumulative impacts. Interpretation of the combined data was difficult because some of the classification parameters refer to differing time intervals in which there is an opportunity for residues to be extracted rather than the magnitude of the impact. For example, there may be periods of the year then wetness class/threat of soil compaction does not impose a restriction on residue harvesting, whereas others, such as acidification, are an assessment of the degree of impact associated with removal. In practical terms, this might translate into opportunities for large scale residue removal within short durations, when the soil is dry, compared to selective removal on acid sensitive sites, but where timing is less critical.

Table 12: Proportion of forest area suitable for forest residue harvesting based on the combination of environmental impacts

Study Area	Suitability assessment based on combined impacts				
	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Unsuitable (S4)	Unclassified
Clashindarroch	0.000	0.076	0.739	0.185	n/a
Morven and Aros	0.000	0.125	0.230	0.643	n/a
Southern Uplands	0.000	0.002	0.700	0.298	n/a
Clocaenog	0.000	0.000	0.930	0.067	0.003
Thetford	0.329	0.016	0.559	0.092	0.004
South Downs	0.032	0.607	0.236	0.111	0.015
New Forest	0.002	0.703	0.142	0.149	0.004

The model outputs are displayed for all the case study areas in the maps document. It was possible to differentiate clearly between opportunities for residue harvesting on upland forestry in the north and west of the UK and lowland forestry in the south. This reflects the different biophysical conditions but, whilst cumulatively the distinction between upland and lowland forestry is reasonably clear, in fact there was considerable variation in the way these cumulative scores were derived.

The acidification risk in the west of Scotland matches more closely those of southern England than with the other upland sites. A large part of the case study area comprises tertiary basalts, which are relatively base-rich, in comparison to the predominantly acid metamorphic and sedimentary rocks of the other case sites in Scotland and in Wales.

The contrast in the soil compaction assessment between case sites in the west area and those in the east was very marked. Large parts of the Morven and Aros area in particular comprise very poorly drained soils (peaty gleys and peat). This factor contributed principally to the large area deemed unsuitable

for residue extraction. The soil wetness class assessment assumes no tree cover, and so the assessment presented here is the worst case. We would not advocate any adjustment to the classification, however, without obtaining further information.

The absence for the most part of any highly suitable areas was a result of the classification relating to soil fertility. Outside of Thetford (including the chalk of the South Downs) there were very few soils with a pH value above 7 (in the surface soil). Even the Thetford values may be anomalous, for data are applied to individually mapped soil polygons and, whilst the data have been considered only for forest areas, the polygon (and therefore soil attributes) may be dominated by agricultural land. The broad categories of soil fertility classes therefore require further consideration. The pH 5-7 range is wide and the impact on soil fertility following residue removal will differ between the soils at either end of this range. However, this dataset was developed originally to provide data to the Forestry Commission on soil fertility and tree growth.

5.8 Analysis of tree cover type

The tree-cover within the case study areas in Scotland is dominated by conifers. In the east and south study areas particularly, the extent of broadleaved and mixed woodland are very small indeed (Table 1) and meaningful comparison of the respective environmental impacts of residue removal from nearby broadleaved and coniferous woodlands is not possible.

In the South Downs and New Forest broadleaved woodlands dominate the forest area accounting for 84% and 74% of forestry respectively.

Whilst Clocaenog and Thetford might be perceived as largely commercial coniferous forests, in fact, there are substantial areas of broadleaved woodlands, with 33% and 27% respectively. Whilst many of the broadleaved trees are in small scattered blocks, clearly, in total, they represent a considerable part of the potential woodfuel resource.

In the Morven and Aros study area, 17% of the forest cover is of broadleaved woodland and this site has been used to illustrate a comparison of suitability for residue harvesting between woodland types (Table 13).

Table 13: Comparison of suitability, for harvesting of forest residues, between broadleaved/ mixed woodland and coniferous woodland in Morven and Aros study area.

Suitability class	Limitation on suitability class	Broadleaved/ mixed woodland (%)	Coniferous woodland (%)
S1 and S2	Highly or moderately suitable	6.9	12.5
S3	Marginal on one impact	15.2	13.8
S3	Marginal on two or more impacts	16.8	9.2
S4	Unsuitable on one impact	46.4	60.9
S4	Unsuitable on two or more impacts	14.8	3.4

The data illustrate broad similarities between suitability assessments for the different woodland types, which was contrary initially to the expectations of the project team. Broadleaved woodlands were anticipated to predominate on the better soils and, as a consequence, a larger proportion of the sites would have cumulative suitability scores at the lower end of the range. Some of this apparent discrepancy can be attributed to the coarseness of the underlying soils data. Most of the land with the highest scores, indicating unsuitability for residue harvesting, on the grounds of two or more impacts, had a wetness class of V or VI and posed an unacceptable risk of sediment transport to water courses. This combination of attributes is unlikely in reality. This is probably an artefact of the under-pinning data: the coarseness of the soils data has not delineated the very steep gullies where broadleaved woodland is often found. Similarly, marginally suitable slopes, between 10 and 25°, which might be trafficked, we again consider that soils of wetness class V or VI are unlikely, which imposes greater restrictions than might be experienced in reality.

5.9 Sensitivity analysis using different resolution soils data

The output from the modelling relied heavily on the quality of the 1:250 000 soil map and the interpretations made from it. More detailed soil maps at the 1:25 000 were available for some of the study areas and a comparison of the outputs generated using higher resolution data were considered in order to assess the confidence which might be placed on the coarser data. The Southern Uplands and Thetford study areas were used for this comparison.

The 1:25 000 soil data were available for the major woodland areas. In the Southern Uplands study area most of the coniferous woodland (6716 ha of a total of 7353 ha) is covered by this higher resolution data. The remaining 700 ha have been excluded from the subsequent analysis, allowing a direct comparison with the output produced from the 1:250 000 scale data. Similarly, at Thetford digitised soil maps were available for the main forest blocks only.

In general terms, there was a good correspondence between the model outputs generated from both soils datasets. The same cumulative numerical code of suitability may, however, be derived from a number of different combinations of impacts (Section 4.5.4). It was important, from the perspective of making valid comparisons between the outputs, that it was the same combinations of individual impacts which produced the same cumulative suitability class. Had different environmental impacts arisen serious doubt could be cast on the quality of both soils datasets. In the Southern Uplands the modelling produced the same top four cumulative suitability 'scores', representing the same four most common combinations of environmental impacts, irrespective of which soils data were used. Combined, these accounted for approximately 60% of the Southern Uplands forest area assessed.

Another way of comparing the outputs was to determine the amount of forestry land within different ranges of cumulative suitability classes. The results are presented in Table 14 and Table 15 demonstrating a very high correspondence between outputs for the broad categories (S1 to S4). However, at Thetford, within areas of marginal suitability for forest residue

extraction (S3) there were substantial differences, between the two data scales, in the number of restricting impacts.

Table 14: Comparison of the use of 1:250 000 versus 1:25 000 soils data, on the modelled suitability for harvesting of forest residues, in the Southern Uplands study area.

Suitability class	Limitation on suitability class	% forest area (based 1:250 000 soils data)	% forest area (based 1:25 000 soils data)
S1 and S2	Highly or moderately suitable	0.2	2.3
S3	Marginal on one impact	14.9	12.8
S3	Marginal on two impacts	33.7	34.1
S3	Marginal on three or more impacts	21.0	18.5
S4	Unsuitable on one impact	25.3	29.6
S4	Unsuitable on two or more impacts	4.9	2.6

Table 15: Comparison of the use of 1:250 000 versus 1:25 000 soils data, on the modelled suitability for harvesting of forest residues, in the Thetford study area.

Suitability class	Limitation on suitability class	% forest area (based 1:250 000 soils data)	% forest area (based 1:25 000 soils data)
S1	Highly suitable	33.1	30.1
S2	Moderately suitable	1.6	0.4
S3	Marginal on one impact	56.1	9.4
S3	Marginal on two impacts	0	55.8
S3	Marginal on three or more impacts	0	0.1
S4	Unsuitable	9.2	4.1

The major source of difference in the outputs was a result of a higher resolution of soil fertility. The original analysis used data with a single value attributed to each 1 km grid square. At 1:250 000, combinations of soils are often represented as soil complexes, but at 1:25 000, fertility values were attributed individually to areas differentiated by soil series. Discreet areas for each soil series appeared as polygons which present a more realistic representation of the spatial arrangement of soils. Hence soil fertility is the one attribute where the use of the 1:25 000 scale data would enhance the precision and accuracy of the output. Despite these potential sources of error, the comparisons indicate that for broad-scale assessment of suitability class - for which the model was intended - the larger scale data are sufficiently robust. However, some further investigation of the importance of the scale of underlying data is required should the model be developed nationally.

5.10 National Soil Inventory Validation

The use of national soil inventory data as the basis of the models was rejected principally for reasons of non-uniformity between the datasets of Scotland and England and Wales. Nor was it clear whether either of two approaches tested, as means to maximise the available soils data, were appropriate. Without extrapolation there were too few data on which to base a model. However, the point data may be used to validate the derived datasets employed in the models: this was done for the soil attributes of fertility (pH), erosion (slope) and compaction (wetness class) at the three case sites in England and Clocaenog in Wales. The results summarised in Table 16 were disappointing. However, the comparisons were based on too few data to draw meaningful results or challenge the validity of the modelling approach adopted.

Table 16: Proportion of forest area suitable for forest residue harvesting based on the combination of environmental impacts

Study Area	Attribute	Number of datapoints within forested area	Datapoints matching modelled output	Datapoints over/under estimating modelled output by 1 suitability class	Datapoints over/under estimating modelled output by 2 suitability class
Clocaenog	pH	6	5	0	1
	Slope	6	3	2	1
	Wetness	6	2	3	1
Thetford	pH	9	4	4	1
	Slope	9	9	0	0
	Wetness	9	9	0	0
South Downs	pH	5	1	3	1
	Slope	5	4	1	0
	Wetness	5	0	2	3
New Forest	pH	4	3	1	0
	Slope	4	3	1	0
	Wetness	4	4	0	0

6 IMPLICATIONS OF IMPACTS

6.1 National Implications of Modelled Output for Case-Study Areas

The choice of case study areas was commended in peer review for its coverage of the range of forest sites encountered in Britain. However, the areas represent only 2.8% of the forest area of Great Britain. We have elected not to include a simple numerical extrapolation of the model outputs to estimate the resource for the whole country. It is possible, however, to consider the model outputs against a national survey, derived from expert opinion and reported by forest district, of the potential woodfuel resource from traditional forestry.

McKay *et al.* (2003) undertook a comprehensive analysis of the woodfuel resource of Great Britain from all sources: forests, sawmills, urban areas, roadsides, power line routes and short rotation coppice. The existing forest resource (represented in woodland areas >2 ha) was determined from the Forest Enterprise database of the publicly-owned forest and the National Inventory of Trees to provide data from privately-owned forest. The project derived relationships between stem wood and other components of tree biomass. These relationships were combined with forecasting models. Expert opinion was used to consider how site and environmental constraints affected the fraction of the biological production that could be extracted from harvesting sites. These data were extrapolated to all forests in the district. The case study data from this project have been compared with the data contained in McKay *et al.* (2003) for the forest district in which they lie (Table 17). The case study data present the percentage forest area for residue extraction based on suitability classes (as reported at Section 5.7). The highly and moderately suitable categories have been combined and presented with the data for marginally suitable and unsuitable land. The range of data from the report of McKay *et al.* (2003) result from differentiation between spruce, pine, other conifers and broadleaves and by combining separate assessments for state and private forest land.

Table 17: Comparison of availability of forest residues determined by geographical model (from this project) against expert knowledge (reported in McKay *et al.*, 2003).

Study area	FC district in which study area located	% high/moderate suitability	% marginal suitability	% unsuitable	% residues available in district (McKay)
Clashindarroch	Moray	7.6	73.9	18.5	0
Morven and Aros	Lorne	12.7	23.0	64.3	13-21
Southern Uplands	Scottish Borders	0.2	70.0	29.8	0-40
Clocaenog	Coed Y Gororau	0.3	93.0	6.7	20-59
Thetford	East Anglia	34.9	55.9	9.2	19-62
South Downs	South East	65.3	23.6	11.1	46-61
New Forest	New Forest	70.9	14.2	14.9	16-38

Broadly, the project team was reassured by this comparison. Whilst peer review considered the model outputs to be excessively pessimistic, the GIS models universally under-estimated the proportion of forest land unsuitable for residue extraction, relative to an expert system. However, the reviewer’s analysis related principally to the allocation of such a large proportion of forest to the marginally suitable category, when this was based principally around sustainability of soil fertility. Our interpretation of this issue is not that our approach is unduly cautious but rather that the models are insufficiently sensitive in considering sites such as the Southern Uplands and Clocaenog, for one might in fact interpret our results as being overly ambitious, as they offer potentially the majority of the forests for residue extraction.

Clashindarroch is close to the borders of the Forest Districts of Moray, Buchan and Kincardine. The reported availability of residues in Kincardine district, as determined by expert system, was in the range 21-30%. The data for Morven and Aros coincide closely with those of the district. In contrast to the upland

sites, estimates for the lowland sites presented in this report appear overly optimistic, in comparison with the expert system. The most likely explanation lies in ecological or other environmental designation of sites which would make them unsuitable for residue extraction. Our models consider only physicochemical impacts.

We conclude that we have the basis of a system which stands comparison with an expert system. We consider that one of the problems of comparing the expert and modelled systems is simply one of nomenclature. Land which we have termed 'marginally suitable' for residue extraction may conjure different reactions in the minds of different users. The project team was supportive of the expert system as a mechanism for audit of forest residue stock in 2003, which may be projected some years hence. We see no need, therefore, to try to extrapolate our own data and would instead direct readers to the report of McKay *et al.* (2003), available at <http://www.woodfuelresource.org.uk>. However, we contend that the modelling approach is potentially much more flexible and would enable direct, true geographic interpretation. We believe that it should be developed nationally to enable national, regional, or location-specific assessment.

6.2 Implications for Change of Impact Resulting from Residue Extraction

The project team was required to consider how environmental impacts might change as a result of the removal of forest residues. This is far from straightforward because some impacts may be felt immediately and others may accumulate over several rotations. This is a consequence of the fact noted, in Section 5.7, that some of the classification parameters refer to differing durations of opportunity for residues to be extracted and others the magnitude of the impact. This illustrates the difficulty, in the modelling approach adopted, of establishing thresholds which will be satisfactory for all users. Examples from Section 5.7 demonstrate this difficulty.

Wetness class/threat of soil compaction may impose a seasonal restriction on residue harvesting and the impact threshold reflects the length of the 'window' when removal is feasible. However, whilst the length of this window is based upon long-term climatic data, in practice unpredictable, sudden changes in the

weather may result in adverse impacts on first extraction of residues. In contrast, impacts such as acidification, would not necessarily be evident after a single residue harvest even on acid sensitive sites. This and potential fertility constraints have a potential cumulative impact (over multiple harvests).

Clearly, interpretation of the various impacts involves a complex combination of risk and hazard. This report advocates throughout that users should interpret the individual layers of environmental information. We anticipated that users in the forestry or energy generation industries would have the sophistication to interpret the output in this way. If the model were presented as a decision-support tool we would agree that there would be a need for hazard and risk to be unified into a common output but we do not believe that it would then ever receive the widespread approval of its users, as was suggested by peer review. For the intended purpose of the model (to assist policy makers or energy generators) we consider that the adopted thresholds provide appropriate long-term projections, involving multiple harvests. It makes it impracticable, however, to consider how current environment impacts may change, in the short-term (to 2020) as a result of removal of forest residues.

We have noted at Section 3.3 that short-term impacts will be those imposed by the prevailing policy and economic climate.

7 KNOWLEDGE GAPS

7.1 Limitations of the model

The model developed is restricted to physical and chemical implications of residue harvesting and is currently simplistic in its approach to a number of the issues assessed. For example, soil fertility is derived from soil pH. Soils of high pH are rich in base cations and the corollary is true, but this is a crude approach particularly as the review of literature demonstrates that data relating to specific ions, principally phosphorus and calcium, are likely to be of greatest importance to sustainable forest productivity following forest residue harvesting. The buffering capacity of base cations is also the key to maps of critical load.

Peer review of the parameters considered in the model confirmed their appropriateness but questioned the usefulness of employing pH as a measure for soil fertility. The project team had expressed similar reservations but the beauty of a digital model is that it presents layers of information, which may be considered individually or cumulatively. Ideally the user of the model would be presented with a menu of datasets from which a selection would be made. User dissatisfaction with the choice of datasets would indicate research requirements.

We are very aware that the model is limited to consideration of residue harvesting with or without brashmats and that apportioning brash between soil protection and harvesting is possible. Nonetheless we should not wish for this handicap to be over-emphasised. By presenting separately the data for the parameters on which the model is based we consider that appropriate interpretation is possible and that it would be possible, using residue yield data and the output of proposed research (Section 7.4), for this to be developed into the model.

7.2 Monitoring Strategy to Test the Model

Verification determines that a model is true, that is the model code, or the mechanism of summation of the parameters, perform as intended. The model has been verified through collaborative working between institutions in

Scotland and in England. Validation is a check on the strength of the model against observed data. We observe, in Section 6.2, that ideally the model would require testing against field data over multiple rotations but clearly this is not a feasible approach. Validation is possible therefore only by peer review and the confidence of the model's users in the selection of parameters and of the thresholds between suitability rankings.

Single peer review of the original draft of this report has been greatly beneficial in providing potential user reaction to a model of this kind. It highlighted areas of perceived weakness in one of the adopted datasets and in the threshold values of this dataset in particular.

The following proposed areas for development of the model and related research needs are those of the project team. The value of our suggestions should be tested against wider industry reaction to the model and the usual safeguards of broader peer appraisal of research proposals.

7.3 Future development of the model

We recognise that the models adopted are simplistic in a number of key areas.

7.3.1 Sustainable soil fertility

The literature indicates that finding soil variables which explain tree growth/productivity is unreliable. Therefore, incorporating a prediction of future impact in response to a forest operation is fraught with difficulty. Relating soil fertility to pH was not our favoured approach: we should have preferred to include measures more directly related to nutrient supply, such as C:N and exchangeable cations. Appropriate data sets do not exist, currently.

We elected to include this factor by employing the Forestry Commission dataset on soil fertility for tree growth. The datasets employs soil pH as an indicator of soil fertility. Peer review questioned the wisdom first of utilising these data given the weakness of any relationship to forest soils and secondly, if it were to be adopted, whether the pH thresholds should be adjusted. Our conclusion was to retain the dataset within these case study assessments, for impact should be interpreted relative to retention of residues on site. We agree with the peer review, however, that for future development of the model,

access to the unmodified data is required in order to investigate the benefits of adjusting the threshold values.

If peer review were typical of potential user reaction then this suggests that new, national forest soil survey data are required, to be collected in a systematic and UK-consistent manner.

7.3.2 Critical loads

Values of critical load of acidity were employed in the model. Peer review questioned the categorisation adopted in relation to critical loads, considering whether the project should adopt a more cautious approach to the precautionary principle! We consider our threshold selection to be an appropriate measure of risk, based on the literature review. Whilst assessment of risk is comparable to the other environmental constraints considered within the model, the inclusion of values relating to the exceedence of critical loads, at the case study sites, would have provided a superior measure of the true hazard. Exceedence data were not available for this project, but were the model to be developed for the whole of the UK then it would be appropriate to analyse the impact of assessing the hazard in addition to risk.

7.3.3 Erosion

In the model, erosion risk is a function only of topography. Erosion of bare ground is also a function of soil type. The model assumes that accumulated forest litter and/or the presence of a herb layer provides protection from soil erosion and erosion risk develops only following site disturbance from harvesting traffic. Erosion from the disturbed ground was considered subsequently to be primarily a function of slope. Consequently, if slope were too great for traffic there was no key for erosion from vehicular movements and then erosion was not considered. The same considerations were applied to sediment transport to watercourses. We know that erosion risk is related to soil type and critically that it is episodic in response to extreme rainfall. We should like to develop this aspect of the model by incorporating climatic data.

7.3.4 Development of a national model

Notwithstanding concerns of peer review that the model is dominated by the fertility and acidity, we would advocate development of the model nationally.

Not only have we advised, above, on possible approaches to reconciling concerns relating to the datasets employed but it would also be desirable to identify further advice for the interpretation of the model outputs. We stressed the need (Section 5.7) for users to base interpretation of the combined model output on individual layers of information. An electronically available model would enable users to choose which data layers to adopt. For example, a user may dismiss marginal suitability, determined only on the basis of soil fertility, and determine that an area is moderately suitable for residue extraction. This would not undermine the national approach so long as the data layers adopted were recorded as part of the output.

Whilst we consider that the benefits would be greatest for policy makers and energy generators, with appropriate qualification of the constraints, it could be adopted also be forest managers as a *decision-support* tool. The existing project team possesses the capability of developing a user-friendly front-end to the model, enabling easy access for a given geographic area of the users choosing.

Extending the model presents significant financial constraints unless an understanding was to be reached enabling access to digital elevation models for the UK and agreeing access to the Land Cover Map 2000, held by the Centre for Ecology and Hydrology. Whilst currently, the model is confined to physicochemical impacts, the inclusion of a data layer indicating environmental designations should be considered.

Notwithstanding the conclusions on the suitability of 1:250 000 data at Section 5.9, we advocate further testing on a wider range of site types to determine whether the data perform better in some circumstances than in others.

7.4 Related research needs

The literature review revealed contradictory data on the impacts of WTH and more empirical data are required, particularly related to UK conditions.

The most fundamental data required are those which provide a useable predictor of sustainable soil fertility. The decision to gather new data should be in response to potential user reaction, which may be tested amongst

readers of this report. We considered that the use of a Forestry Commission dataset suggested a measure of forest industry support.

Yield data for residues may be incorporated from the modelled output of the Forestry Commission's Production Forecast/BSORT model, which is based on allometric relationships (McKay *et al.*, 2003). However, this will provide only estimates of mass, and the translation of these data into energy values should be treated with caution. We do not believe that the calorific value of branch wood relative to stem wood has been investigated adequately. Loss of calorific value due to respiration during a period of storage within the forest is possible and requires investigation.

Whilst a number of studies have recorded sediment movement at forest sites, we believe that creating a network of long-term erosion monitoring sites would be beneficial. This would improve understandings of the interactions between soil, climate, vegetation cover and the role of local trafficking damage in initiating erosion. These records may be used to validate data from replicable experiments conducted using soil slopes and a rainfall simulator, from which models may be developed. Provision for such experiments exists, on the largest scale within the UK, at Cranfield University.

Similarly, we would advocate a more rigorous approach to measurements of soil compaction, using replicable laboratory-based testing facilities. Cranfield University possesses unique laboratory facilities for this purpose.

Long-term assessment of biodiversity impacts of forest residue extraction is needed. Popular opinion is very sensitive to higher species and often these indicate impacts within complex food-webs. However, a more practical assessment would be of the soil microbial community and function which can be used to compare the health of sites and ecosystems (for example, Johnston and Crossley, 2002) reliably and within the timeframe, for example, of a doctoral studentship.

8 CONCLUSIONS

Seven case study areas were selected for analysis of their suitability for the harvesting of forest residues. The areas were considered to maximise the representation of soil and climatic conditions on which commercial forestry is practised in Great Britain. A GIS based modelling approach was employed, which for the most part employed existing datasets rather than developing models from original soil parameters. From the model outputs, four classes of suitability for forest residue harvesting were identified *viz.* highly, moderately and marginally suitable, or unsuitable.

Based on cumulative classifications of suitability for forest residue extraction within these representative study areas, we determined that there are limited opportunities, in upland forestry, for the removal of forest residues because of the environmental impacts associated with the activity. This is not surprising, as many of these woodlands, planted in the period from 1945 until the late 1980s were established on relatively poor sites. The soils are predominantly acidic, nutrient poor and often very wet. It is axiomatic that these soils would benefit from the protection afforded by residues during harvesting. In spruce dominated plantations particularly the total quantities of residues may be such that it is possible to form brash mats and harvest a residue excess that is not required for site protection and, therefore, has not been trafficked. Many of the better forestry soils in upland areas, in particular brown earths, occur on steep slopes that may not be trafficked and the issues of WTH are safety led. In lowland forests, in England, better soils occur without the constraint of steep ground and opportunities for residue harvesting are substantially greater.

The final outputs from the models are driven clearly by the individual model parameters and thresholds, and the quality and resolution of the underpinning datasets. The model thresholds are based on an interpretation of scientific findings and understanding and the collective appreciation of the authors of practical aspects of woodland management. Further information on residue yields is required. The implications for yield, of only partial harvesting of residues, require careful consideration of the economic implications.

The underlying ethos to the modelling is precautionary, given the degree of uncertainty and sometimes contradictory evidence from different field experiments from a number of countries. Clearly, therefore, there were some uncertainties associated with different components of the model and how they should be interpreted. The availability of some data and their coarse resolution were also a constraint.

There is a lack of quantitative guidance regarding slope thresholds for soil erosion assessments. The current thresholds reflect the precautionary stance and it might be that they are conservative.

We advocate research projects to provide replicable data to underpin the model. The review of literature underlined the concerns of a number of investigators that their data were site specific. Laboratory based equipment exists, at sufficient scale, to reproduce in controlled experiments, conditions which would enable measurement of the impacts to soil of harvesting without forest residues or measuring the quantities needed for effective protection. Similarly, soil erosion can be measured very accurately using soil slopes and rainfall simulators, using equipment of an appropriate scale. The effect of soil surface protection from vegetation, litter and brash can be determined and the effect of the presence of disturbance as a key for erosion can be measured.

We recommend that the model is developed at a national scale and that this development includes provision for user-friendly interrogation for any grid reference.

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